DESCRIPTIVE ASTRONOMY

AN ELEMENTARY EXPOSITION OF THE FACTS, PRINCIPLES, AND THEORIES OF ASTRONOMICAL SCIENCE

By

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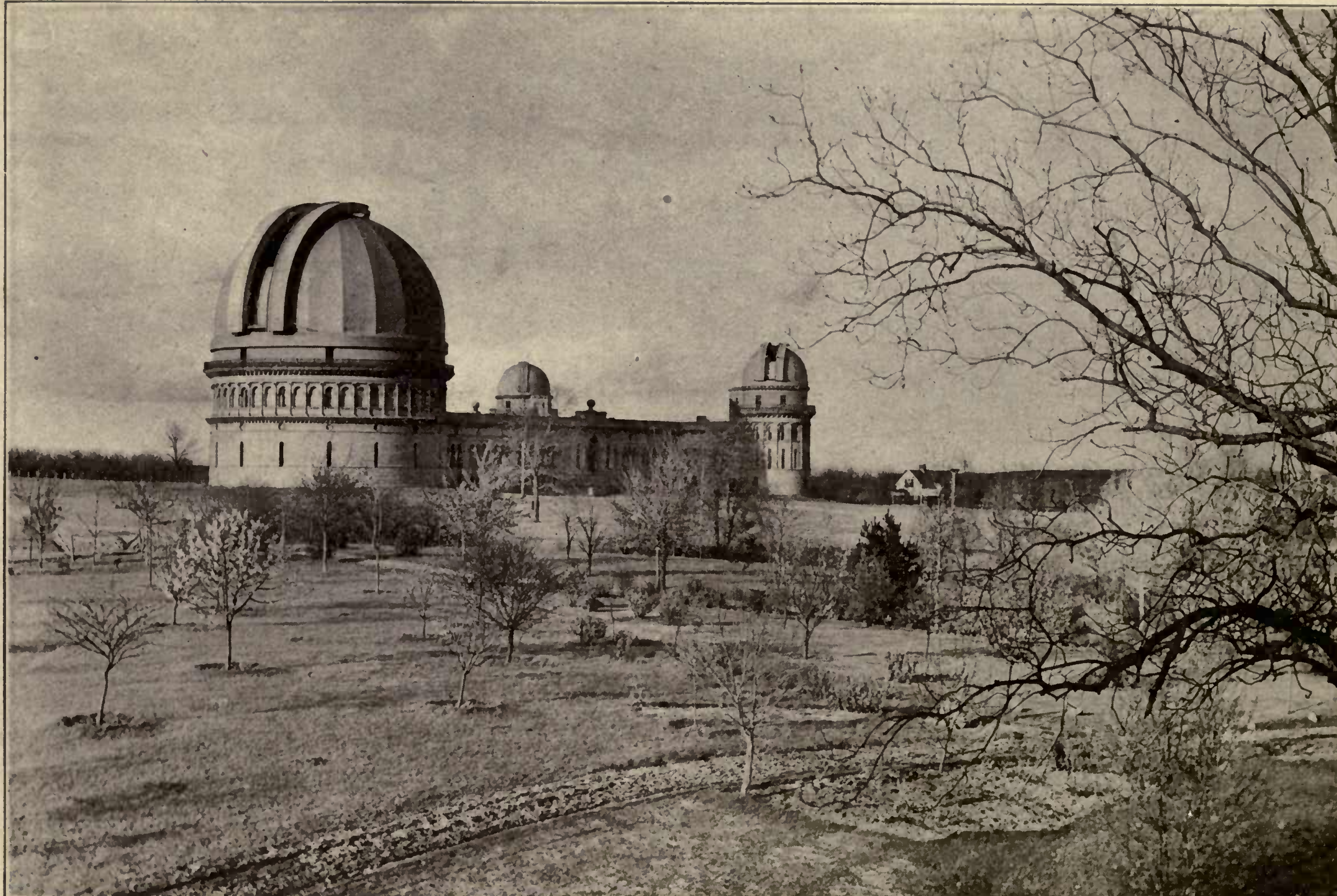

VIEW OF YERKES OBSERVATORY OF THE UNIVERSITY OF CHICAGO, WILLIAMS BAY, WISCONSIN
The big dome at the left houses the 40-inch Yerkes Refraction Telescope

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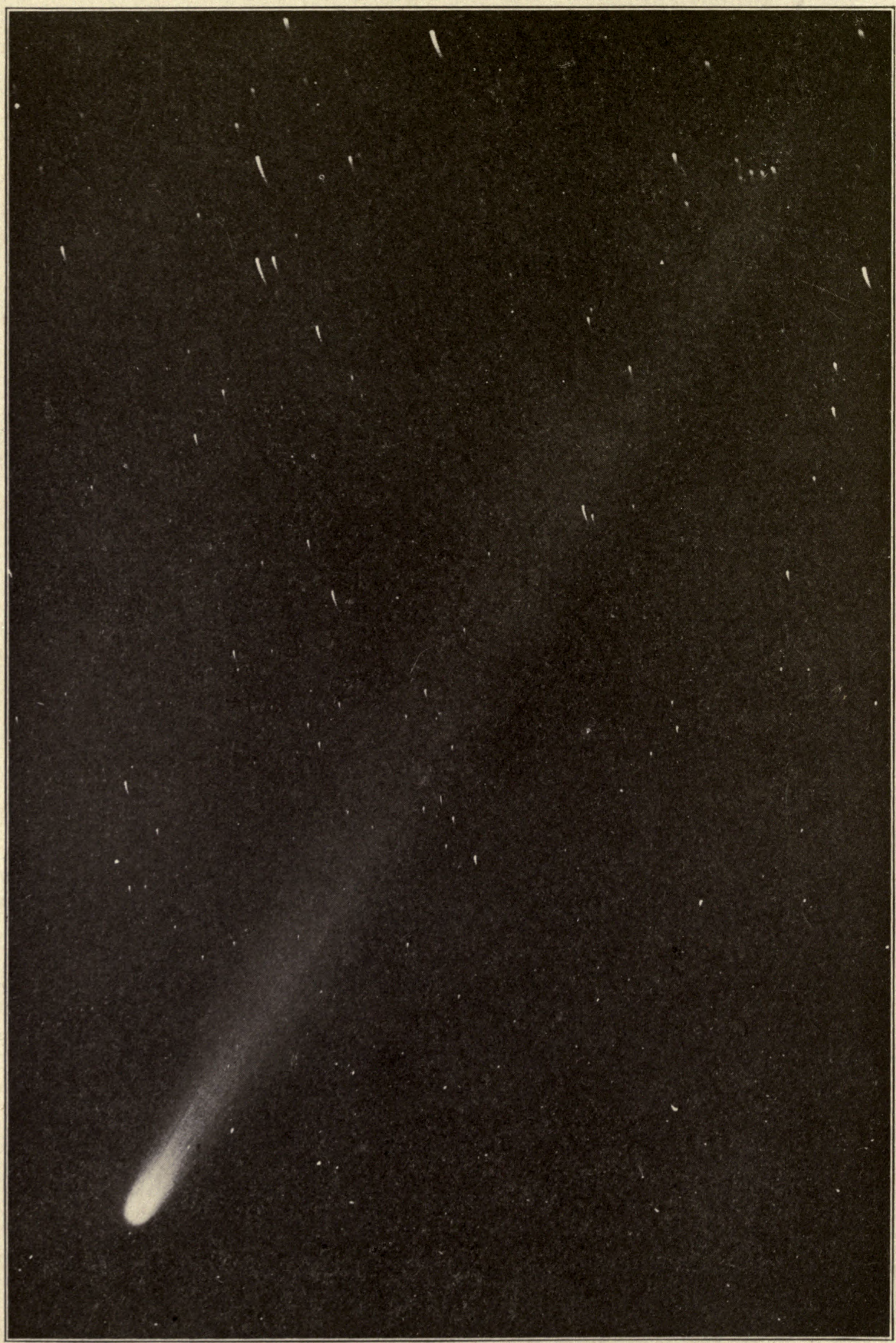


HALLEY'S COMET

This picture was taken at Yerkes Observatory on May 4, 1910, with an exposure of forty minutes. The tail is about 8° long

INTRODUCTION

ASTRONOMY has the glory of being the oldest science. In fact, men first realized from the majestic and relatively simple motions of the heavenly bodies that the universe is a universe of order and, therefore, that science is possible. If the sky had been always cloudy, if observations could not have extended beyond the exceedingly complex and varying terrestrial phenomena, it is probable that many centuries would have passed before scientists would have arrived at the point of view which was necessary for the development of those ideas which have led to the wonderful discoveries of modern times. It is appropriate, therefore, that a book on Astronomy should, among other things, show the connection of celestial phenomena with the important intellectual achievements of civilized man, a phase of the subject which has not been neglected in this work.

¶ There are two chief features to science—the making of observations, and the fitting of them into an organized whole. In this text detailed instructions have been given so that the reader may make such of these observations as do not require the use of instruments, but it is evident that such observations can not add much to the world's knowledge at the present time. However, their performance demands the active instead of the passive attitude of the mind; they give something of the satisfaction that is experienced by an original discoverer; and they make every glance at the familiar stars which fill the sky on a cloudless night one of pleasure. Great care has been taken also to show how the vast multitude of things, which observations have revealed, are linked together into a systematic body of doctrine, and entitle Astronomy to be regarded as one of the most perfect sciences.

¶ Doubtless every person has some more or less definite conception of what the universe is and means, and of his place in it. All the things he knows and experiences modify this conception. The facts revealed in Astronomy—the extent, variety, and lawfulness of the physical universe; that man has in his body the elements of which the infinitely distant stars are composed; that he is but a part of the universal order—effect profoundly his philosophy; and this has been borne in mind in setting forth modern ideas of how tenuous nebulas evolve into finished worlds.

THE GREAT YERKES 40-INCH TELESCOPE
The dome is revolved by machinery and the entire floor is raised or lowered to suit the inclination of the telescope tube

ASTRONOMY

PART I

PRELIMINARY CONSIDERATIONS

The Value of Science. In an age when the world is so largely run by the results of scientific effort it is almost superfluous to speak of the value of science. If the things which science has contributed to our everyday use and which make life at the present time pleasant for us were removed, we should speedily understand the immense debt we owe to it. One has to think only of the means of transportation, communication, and illumination to see how very important it is for us. These things are so well known that they do not need emphasis.

There is an indirect result in the work of scientists which is not so generally understood, and to which we seldom give any consideration. Science has revolutionized our mode of living, that is, it has given us a better food supply than any people ever had; because of it, we are better sheltered and clothed than any people ever have been; our whole mode of living is more sanitary than that of any other people has been; and these facts will eventually result in marked physical changes in mankind as the generations go by. Thus, while we are apt to consider that science pertains largely to the inanimate part of the universe, we see that it is not only of the highest value indirectly to the organic portion, but to man as well. If we are considering things in the long run, this latter may be the one respect in which it is most valuable.

It is a common opinion that science is distinguished from the fine arts and, in fact, is opposed to them. Science and the fine arts are very often supposed to be the antithesis of each other. But one of the results of science has been that it has made us immensely more efficient than we were before, and through its teachings we are enabled to provide the necessities and even the luxuries of life in much less time than was possible before its modern development.

The leisure which has been secured thereby will enable us to turn our attention to the arts and undoubtedly in the future to achieve greater things in this direction than would otherwise have been possible.

It is a mistake to regard science in itself as the opposite of art. There are in all branches of science harmonies and beauties which appeal strongly to those who fully understand them. The great scientists have often expressed themselves as deeply moved by the esthetic side of their subject.

Science also plays an important rôle in the mental discipline. If it is a good thing to think coherently and systematically and to check the results of thinking, then science is of the highest value in the cultivation of the intellect.

Origin of Science. It is doubtful if any important idea ever sprang suddenly into the mind of a single man. The great movements in the world have had long epochs of preparation, and there are evidences that many men were groping for the same idea without exactly seizing it.

The actual dawn of science was in prehistoric times, in the civilizations that flourished in the valleys of the Nile and the Euphrates. In the very earliest records that have come down to us it has been found that those peoples knew much of astronomical phenomena and had coherent ideas of the apparent motions of the sun, moon, planets, and stars. It is perfectly clear from their writings that it was first in observing celestial phenomena that they obtained the idea that the universe was not a chaos. Day and night were seen to succeed each other regularly, the moon passed through its phases systematically, the seasons followed one another in regular sequence; and in fact all the more conspicuous celestial phenomena were seen to recur in an orderly fashion. The dawn of science may be said to have begun when men first clearly perceived that there was order in the universe and that by observations they could discover what it was. It is to the glory of astronomy that its phenomena were of such a character that men first perceived in this realm that we live in an orderly universe.

The ancient Greeks, at a period four or five hundred years preceding the Christian Era, definitely undertook to find from systematic observations how celestial phenomena follow one another. Before their time, observations were, indeed, made extending over long intervals, but without a conscious effort to attain the laws according to which the universe moves. The Greeks determined very accurately the number of days in a year, the number of days in a month, the path of the moon among the stars; they explained the cause of eclipses and learned how to predict them with a considerable degree of accuracy; they undertook to determine the distances of the heavenly bodies, and to work out a complete system that would represent their motions for indefinite time. The idea was current among the Greek philosophers that the earth was round, that it turned on its axis, and among some that it revolved around the sun. Their science, in the modern acceptance of the term, was largely confined to the study of celestial phenomena.

Great Contributions of Astronomy to Science. As has been stated, science started in astronomy. The phenomena of every other science are so complex and depend upon so many varying factors that it would be very difficult for a primitive people to get the idea, *first,* that there were any laws operating in it, and *second,* that they could discover those laws. One has to think only of the complexities in the changes of the weather or in the developments of plant or animal life, to see how hopeless a problem a primitive people would face. It is probably not extravagant to state that if men had not been able to observe celestial phenomena—for example, if the sky had always been cloudy—the dawn of science would have been greatly delayed. It is entirely possible that we should yet be in the most primitive stages of the development of the race.

But we may turn our attention to more specific and direct contributions of astronomy. Every one will admit that mathematics has been of the highest service in all domains of physical science. It is not so generally known that the science of mathematics was largely called into being for uses in explaining astronomical phenomena. Spherical trigonometry was invented in very ancient times for use in solving the problems arising from the celestial sphere. And this is only one of the many examples in which some of the most important mathematical processes have been directly developed as a consequence of the stimulus of a problem set to men in astronomy. While it would undoubtedly be too much to claim that all branches of mathematics have had their original stimulus in astronomical problems, it is certain that without these problems the development of mathematics would have been far different.

The laws of motion are at the very foundation of modern mechanics, and were discovered by astronomers contemplating astronomical phenomena. The conditions on the earth are so complex that it would be very difficult to comprehend the fundamental laws which govern the movement of bodies. On the contrary, the planets move in a vacuum without any friction, and the conditions are so nearly ideal that discovery of these fundamental laws is relatively simple. It is not too much to say that our knowledge of the laws of motion is a contribution from astronomy.

One of the most important influences in modern scientific thought is the doctrine of evolution. Its applications are not only in geology and zoölogy, but they are also in the interpretation of history, sociology, and even religion. It was in contemplating the relatively simple celestial phenomena that the idea of the orderly development from one state to another was first clearly perceived, and the doctrine of evolution was current in astronomical literature more than half a century before it appeared in the writings of Darwin and his contemporaries.

The modern world owes much to the explorations that followed the voyage of Columbus across the sea. It took courage of the highest type to sail for many weeks over an unknown sea in the frail boats of that time. It is perfectly clear that Columbus had good reasons for hoping that he could reach the East Indies by sailing westward from Europe, for otherwise he would not have maintained control of his mutinous sailors for so long a time. His reasons were of an astronomical nature. He had seen the sun rise from the ocean in the east and travel across the sky and set in the west. He had observed that the moon and stars did the same thing. He concluded from the fact that they went down in the west after having pursued regular courses, and rose again in the east in the same courses, that the earth was not of infinite extent but that it was round and could be sailed around. Relying upon the teachings of his observations of the motions of the heavenly bodies, he made the perilous trip across the Atlantic, and that voyage has been of immense importance to the human race.

Present Value of Astronomy. It is easy to see, as has been explained above, that astronomy has made some great contributions to the development of science and civilization; but it is commonly believed that at the present time it is of little practical value to mankind. This is known as a material age and we are apt to consider things valuable only if they are valuable in a material way. But if astronomy is considered from this point of view, we still find that it is very important to us. For example, navigation of the seas is absolutely dependent upon astronomical observations. For more than two centuries France and England gave prizes for accurate astronomical tables that their sailors could use in their journeys over the oceans. And at the present time the positions of vessels are determined in all long voyages by astronomical observations. If one were to make a voyage to the polar regions he would determine his position, and in particular whether he had arrived at the earth's pole or not, by astronomical observations. Consequently, we may say that all the varied and important interests which center in navigation are dependent, even at the present time, upon astronomy.

One might imagine that, even though astronomy is important to sailors, it has little value upon the land. Here, again, the first impression is quite erroneous. Every one recognizes how important it is that our trains be run according to accurate time schedules. It is not so generally known, however, that the time used is based upon astronomical observations made daily. In the National Observatory at Washington observations are made and time is determined and distributed every day over the whole country. More than 30,000 clocks are automatically set every twenty-four hours by the electric signals which are sent out from Washington.

One might ask whether some other method of accurately measuring time might not be devised. The general impression is that a clock might be made to run so accurately that it would serve all purposes. The fact is, no clock was ever made which permanently ran accurately. No two can be made to run exactly alike. In order to obtain a satisfactory measure of time, the ideal conditions under which the heavenly bodies move must be realized. Consequently, a second practical and universal use of astronomy is in furnishing time for mankind.

There are indirect ways in which astronomy is at the present time of great value. For example, if it be conceded that geology is an important science, then astronomy must be considered valuable because it furnishes the foundation for the geologist in telling him of the early state of the earth. If it is important for man to know the laws of change of the weather, then astronomy is again important because the reasons for the changing of the weather are almost entirely astronomical. In this example we have not yet learned fully the laws because they depend partly upon complex conditions that are present here upon the earth. The simple succession of changes that would follow from astronomical causes alone on a uniform earth are modified by great oceans, continental elevations, and chains of mountains. Notwithstanding the complexity of these factors, there is hope of eventually reducing this domain of science to perfect order.

While this is called a material age it is probably not more so than most which have preceded it. And if it is not purely a material age, in estimating the value of any science it is proper to consider its importance aside from its practical applications to the material world. When considered from this point of view astronomy is probably second to no other science. It furnishes man an idea of his place in the universe and has a profound influence upon him in broadening his horizon. It is analogous to the benefits a man derives by traveling on the earth. If he visits various countries he learns many things which he does not directly apply at his home, but which, nevertheless, make him a broader man. And so, while what one may learn about worlds beyond our own can not, on the whole, be applied here, the broadening influence of the wider knowledge is very beneficial. In this way astronomy has had and is having profound influence on philosophy and literature and even religion.

Scope of Astronomy. In astronomy the earth is considered first as a member of the solar system. It is thought of as a member of a family of planets revolving around the sun. Its characteristics as one of the heavenly bodies are investigated. They are, in particular, its shape, its size, its motions, its density, and its interior condition. Then the details of its relations to other members of the system are developed and the corresponding facts for the other planets and the sun are worked out.

There are many secondary members of the planetary system, among which may be mentioned the satellites which revolve around the planets, the comets which revolve around the sun, and a great number of small planets which circulate mostly in the space between Mars and Jupiter. The motions of these bodies and their properties, and their relations to the rest of the system are worked out. The thousands and even millions of stars that fill the sky are found to be suns, and the position and relation of the solar system with respect to the almost countless other systems, particularly the distribution of stars in space, their motions and dimensions, are discovered so far as it is possible. There are also found to be immense cloud-like masses of unorganized world-stuff which we call nebulae, whose number, positions, and relations to the stars are discovered.

In addition to finding out what the universe is at the present time, one of the most important and interesting objects of astronomy is to find out how it originated, through what series of steps it has gone in its evolution, and what changes will take place in it in the future. In particular, the astronomer tries to find out what has been the origin of the earth, how long it has been in existence, especially in a state adapted to the abode of life, and what reasonably may be expected for the future. These great problems of cosmogony have been of interest to mankind from the dawn of civilization, and with increasing knowledge they do not lose their charm.

THE EARTH AS AN ASTRONOMICAL BODY

Astronomical Problems Respecting the Earth. The earth is one of the objects belonging to the field of astronomical investigations. It is in considering it that astronomy has its closest contact with some of the other sciences, particularly with geology and meteorology. Those problems which can be solved for the other planets also, or which are essential in the investigations of other astronomical questions, are properly considered as belonging to the field of astronomy.

The astronomical problems pertaining to the earth are divided into two general classes. *First,* there are those questions which can be answered, at least to a great extent, without considering the earth as a member of the solar system. *Second,* there are those problems which pertain to it as a member of the solar family. Those of the first class are particularly its shape, size, density, rigidity, and its atmosphere; while those of the second class are particularly its motions, the heat and light received from the sun, and its evolution. We shall take up first the questions of the first class.

Proofs That the Earth Is Round. It is a matter of common knowledge that the earth is approximately round, but few can give the reasons for believing it. One of the characteristics of science is that it gives the reasons for its conclusions, and consequently we shall consider the methods by means of which we have proved the sphericity of the earth.

The most commonly stated reasons are that the earth has been circumnavigated and that the surface is apparently convex. While this proves that the earth is not an infinite plane, as the ancients believed it was, it does not prove it is actually round; for these conditions could be satisfied if its surface were any closed, convex figure, even departing very widely from a spherical form. There are better reasons for believing that the earth is actually very nearly spherical. In taking them up we shall first suppose that it is actually a perfect sphere, and then later consider its slight deviations from the globular form.

The simplest and most certain proof of the globular form of the earth is that the plane of the horizon, or the direction of the plumb line, changes by an angle which is directly proportional to the distance traveled along the surface of the earth, whatever be the starting point, direction of travel, and distance traveled. This statement needs some amplification. Let us suppose first that the earth is a sphere and show that the statement is true.

In Fig. 1, let the circle represent the earth whose center is at C, and let us suppose that the stars are very far away from it compared to its size. Suppose the line CP points to the pole of the sky. Suppose an observer is at O_1. He will observe the pole in the direction O_1P_1, which is parallel to CP if the stars are supposed to be infinitely far away compared to the size of the earth. The plane of his horizon is H_1. If he stands at O_1 and looks north he will look in the direction H_1. The angle between the plane of the horizon to the north and the line from the observer to the pole is a_1.

Now let us suppose he travels northward to point O_2. Then the direction to the pole becomes O_2P_2, which is again parallel to CP. His horizon in this case is H_2. The distance of the pole above the horizon is now the angle a_2. He has gone along the surface the distance O_1O_2, which subtends the angle α at the center of the earth. We wish to prove that the direction of his horizon is changed by the same angle. This follows at once because the lines H_1 and H_2 in the figure are, respectively, perpendicular to CO_1 and CO_2, and therefore by plane geometry the angle between H_1 and H_2 is equal to the angle between CO_1 and CO_2; that is, the change of direction of the horizon is equal to the angular distance the observer has traveled along the surface of the earth. If the earth is spherical, the actual distance along the surface in miles is proportional to the angle subtended at the center. Consequently, the original proposition is verified.

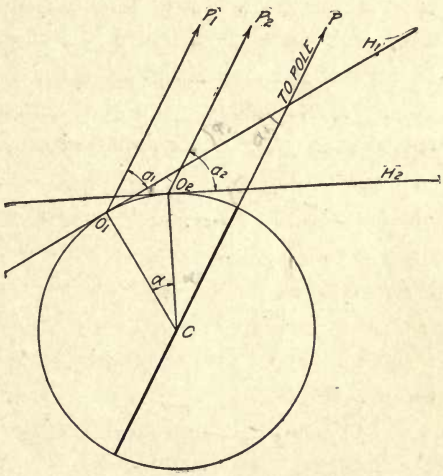


Fig. 1. A Diagram Showing That the Elevation of the Pole of the Sky Varies Proportionally to the Distance Traveled Along a Meridian

There is no other figure than the sphere for which the plane of the horizon will change proportionately to the distance traveled. Consequently, if it is found that as one travels over the surface of the earth the change in direction of the plane of the horizon is in direct proportion to the distance he travels, it proves that the earth is an exact sphere. In Fig. 1, the question was considered only for a motion north and south. The reason for this was that the north star remains fixed in the sky while the other stars appear to move around the earth in diurnal circles just as the sun and moon do. Therefore, it is simpler actually to make the observations for northward and southward motion, and it is also easier to understand the matter. However, in order to show that the earth's curvature is the same in every direction, it is necessary to prove the proposition in the general form given at the beginning.

That this is the simplest method of proving the shape of the earth is supported by the fact that it was the one first discovered and used. The Greek astronomer, Eratosthenes, more than two hundred years B.C., noticed that the north star appeared to be higher when he was in Greece than it did during his journeys farther south in Upper Egypt. He correctly interpreted this as meaning that the earth was convex, and he assumed it was spherical. In fact, he went so far as to try to find the size of the earth by measuring the distance he had to travel over its surface to cause the pole star to change its elevation above the horizon by one degree. While at that very early date correct ideas of the shape of the earth were entertained by a few and attempts were actually made to find its size, nevertheless the belief in the roundness of the earth perished because of the lack of the scientific spirit and the mysticism of antiquity. There was no general acceptance of the fact that the earth is round until after Columbus had crossed the Atlantic and his immediate followers had circumnavigated the globe.

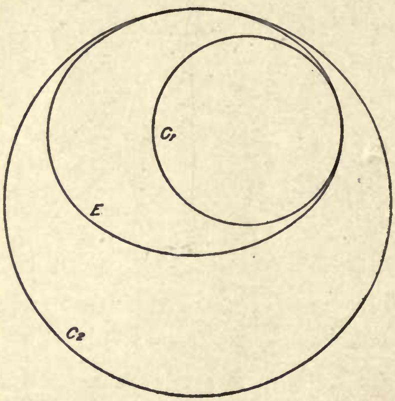


Fig. 2. The Curve E Is a Section of the Flattened Earth; C_1 Is a Circle Having the Curvature of the Earth at Its Equator, and C_2 One Having the Curvature of the Earth at Its Pole

Oblateness of the Earth. In the preceding section a method of proving the sphericity of the earth was given, providing the earth were actually spherical. If it is not perfectly round, obviously the method ought to reveal this fact. As a matter of fact it has been found that the earth is slightly flattened at the poles and bulged at the equator. We shall now see how the observations have shown this to be true.

Let us first suppose that the earth is flattened, as has been stated, and see what the observation should show. In Fig. 2, let the curve E represent a section of the earth through its axis and perpendicular to its equator. Let the circle C_1 be a circle which has the same curvature as the earth at its equator, and let the circle C_2 be that one which has the same curvature as the earth at its pole. It is clear from the figure that C_1 is smaller than C_2. Consequently, if one were to go a degree north or south on the earth at its equator he would be going a distance equal to one degree on the circle C_1, and if he were to go a degree north or south on the earth near the pole he would be going a distance equal to one degree on the circle C_2; that is, a distance corresponding to one degree as measured by the difference in direction of the pole is less at the equator of the earth than it is at the pole of the earth if the earth is flattened. On the other hand, if the earth were elongated in the direction of its axis the opposite result would be true.

The actual shape of the earth was under discussion for a long time, the English, following Newton, taking the position that it is flattened at the poles and bulged at the equator; and the French, who were generally opposed to the English in everything, taking the position that it is flattened at the equator and bulged at the poles. About 1745 the French measured an arc in Lapland near the Arctic Circle, and another in Peru near the equator. They found definitely that the arc one degree in length was longer in Lapland than it was in Peru. This proved beyond any question that the earth is flattened at the poles and bulged at the equator, and besides it gave the amount of the flattening.

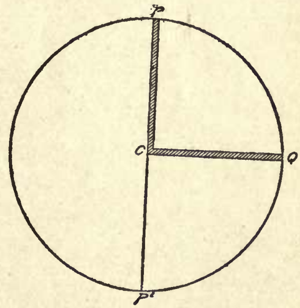


Fig. 3. Newton's Canal Proof That the Earth Is Oblate

Newton's prediction that the earth would be found by observations to be oblate is one worthy of notice. Relying on the fact that the earth rotates he was able to prove it. In Fig. 3, let *PP′* be the axis around which the earth rotates, and *Q* a point on its equator. Newton imagined a canal constructed from *P* to *C*, the center of the earth, and then from *C* to *Q*. The rotation of the earth has no effect upon the weight of the water in the canal *PC*. But the rotation decreases the weight of every unit volume of water in the canal *CQ*, the amount of the decrease depending on its distance from the axis. Now, if the two canals are to be in equilibrium the pressure of *PC* at *C* must be exactly equal to the pressure of *QC* at *C*. Since each unit volume in *QC* exerts a less pressure than the corresponding one in *PC*, it follows that the canal *QC* must be longer than the canal *PC*. It is not a simple matter to find how much longer it must be, yet Newton solved the problem and his results have been verified.

There is a third method of proving the existence of the equatorial bulge of the earth. The moon is kept in its orbit around the earth by the earth's attraction for it. Now, the attraction of the earth on the moon is not quite the same if it is oblate as it would be if it were strictly spherical. This variation in attraction will cause a corresponding small change in the motion of the moon. When the amount of the equatorial bulge is known, the irregularities produced by it on the motion of the moon can be computed. As a matter of fact they have been computed and it has been found that the motion of the moon has exactly those irregularities which it should have if the earth were oblate, thus verifying the fact of its oblateness.

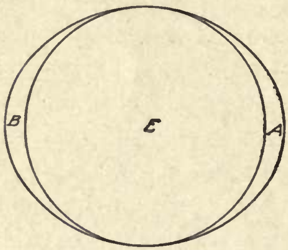


Fig. 4. The Moon's Attraction for the Equatorial Bulge of the Earth ffects Rotation and Proves That There Is a Bulge

Conversely, the attraction of the moon for the earth is different from what it would be if the earth were spherical.

In Fig. 4, let E represent the largest sphere which can be cut out of the flattened earth. The attraction of the moon has no effect on the rotation of the sphere, but its attraction on the equatorial bulge, A and B, does have an effect upon the rotation of the earth. This effect is actually observed and proves that the earth is bulged at the equator. Not only do all these proofs agree in showing that it is oblate, but they also agree in the determination of the amount of the oblateness.

It is not sufficient to say that the earth is flattened at the poles and bulged at the equator, but it is necessary to describe more exactly its form. In order to do this we must define the curve called an ellipse, which is represented in Fig. 5.

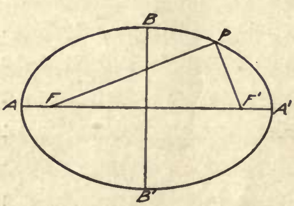


Fig. 5. An Ellipse of Which the Foci Are F and F'

The ellipse is an oblong, closed curve, such that the sum of the distances from two fixed points within, F and F', to any point P on its circumference is always the same. It follows from this definition that a convenient way to draw it is to set two pins at F and F' in the drawing-board and to tie the ends of a string, whose length is somewhat greater than the distance FF', to them. Then if a pencil is put in the string at P and held tight, the circumference of the ellipse can be easily traced out.

If the ellipse be rotated around the diameter BB' it generates a solid which is called an *oblate spheroid.* Its shape is roughly like that of an orange. If it were rotated around the longest axis, AA', it would generate what is called a *prolate spheroid,* whose shape is similar to that of a long watermelon. Now, the shape of the earth is very nearly that of an oblate spheroid, though the amount of flattening is so small that if it were drawn to scale it would appear to the eye as sensibly spherical. There are some slight deviations from the oblate spheroidal figure due principally to the continental elevations and the irregularities in the distribution of matter.

Size of the Earth. The measurements of the arcs on the surface of the earth not only prove its shape but furnish us directly its size. It has been found in this way that its mean diameter is about 7,910 miles. The equatorial diameter is about 27 miles greater than the polar, owing to the flattening of the earth. According to the most accurate observations and computations so far made, the equatorial diameter is 7,926.7 miles, and the polar diameter 7,900 miles. According to this the equatorial circumference of the earth is 24,902 miles.

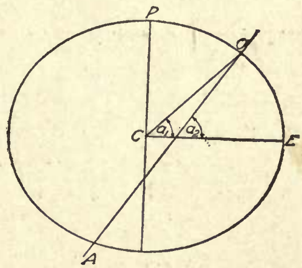


Fig. 6. The Geocentric Latitude Is a_1 and the Astronomical Latitude Is a_2

From the figures given above it is found that one degree in latitude at the earth's equator equals 68.7 miles, and at the pole, 69.4 miles; that is, a degree at the pole is about one per cent longer than one at the equator. In longitude, one degree at the equator equals 69.7 miles. In latitude forty degrees, one degree in longitude equals 53.4 miles. In latitude sixty degrees, one degree in longitude equals 34.9 miles and, of course, at the pole there is no such thing as longitude.

Different Kinds of Latitude. Since the earth is not a perfect sphere, a perpendicular to its surface (*i.e.,* water level surface), at any point except on the equator or at the poles does not pass through its center. This gives rise to different kinds of latitude.

In Fig. 6, let P represent the pole of the earth, E a point on its equator, and C its center. Suppose an observer is at O and that OA is perpendicular to the surface at O. The *geocentric latitude* is the angle $ECO = a_1$. The astronomical latitude, *i.e.*, the latitude which would be found by astronomical observations, is the angle a_2. It is seen from the figure that the astronomical latitude is a little greater than the geocentric latitude.

Density of the Earth. In measuring the densities of solids and liquids it is customary to use water at its greatest density as the standard. It is necessary to state that the density of water at a given temperature is used as the standard because it varies with the temperature. If we start with a very high temperature the density increases as the temperature falls until it reaches about 39° F., after which the density begins to decrease. If this were not so, ice would be denser than water and would sink instead of float. When it is said that the density of rock is three, it is meant that a given volume of rock weighs three times as much as the same volume of water at its greatest density.

It is a simple matter to determine by direct examination the densities of those materials on the earth which are so near its surface they can be actually reached. But when it is understood that the deepest borings in the earth reach to a depth of about two miles only, which is only $\frac{1}{2000}$ of the distance to the earth's center, it is clear how small a part of the earth's mass comes directly under our observation. It is, therefore, necessary to discover some indirect method of finding the density of those parts which lie so deep we can not reach them.

The volume of the earth being known, its density can be found provided we can discover some way of finding its mass. *The masses of all astronomical bodies are found by their attractions for known bodies.* The attraction of the earth for masses at its surface is what gives them weight. It is possible, though it is a very delicate experiment, to compare the attraction of the earth for a small ball with that of a large ball for the same small one. The delicacy of the experiment comes from the fact that the force of gravity is so feeble that it is with great difficulty that the attraction of the large ball for the small one can be measured. Let us suppose, however, that it has been measured, as is actually the case in many experiments which have been carried out, and let us see how the mass of the earth can be determined. The attraction of one body for another depends upon two chief factors, viz, the mass of the attracting body and its distance from the attracted body. Now, in the experiment of comparing the attraction of the earth with that of a large ball for a small ball, the distances of the earth and the large ball from the small one are known. The relative attractions are measured. The density of the large ball and, therefore, its mass are known. The only unknown in the proportion is the mass of the earth; or, since its volume is known, the only unknown is its density. By means of these measurements and the discussion of them, it has been found that the average density of the earth taken through and through is about 5.5. The average density of the surface rock with which we are familiar is from 2.75 to 3. This means that the interior is, on the whole, considerably denser than the surface rock. Two explanations of this are possible: *First,* the material of which the interior is composed may be largely of dense substances; *second,* it may be that the great pressures which prevail in the interior are sufficient to squeeze ordinary matter to such an extent that its density is increased enough to account for the greater density of the interior.

The pressure on the interior of the earth is enormous. The weight of a cubic foot of water is, in round numbers, 60 pounds, and of the surface rock approximately 180 pounds. If we stretch this cube out into a parallelopiped, whose base is one inch square, its height will be 1,728 inches (since there are 1,728 cubic inches in a cubic foot), or 144 feet. The pressure of this column on its base will be its weight of 180 pounds. The pressure on such a column of one-inch cross-section at the depth of one mile will be $\frac{5280}{144}\times180=$ 6,600 pounds. The pressure at the depth of 100 miles, therefore, will equal 330 tons per square inch, which is a very moderate depth when the earth as a whole is considered. It is easily conceivable that these enormous pressures are sufficient to give ordinary matter a density of 5.5, and consequently there is no reason to believe from these considerations that the material of which the interior of the earth is made is, on the whole, radically different from that which is near its surface.

Condition of Interior of the Earth. It has been very generally believed until recent times that the interior of the earth is in a fluid state, owing to the high temperatures prevailing there. It has been found that the temperature rises about 1° F. for every 50 to 100 feet that one goes down in the earth. The rate of increase of temperature varies greatly at different places. But taking the slowest rate observed, it is seen that if it continues to great depths the temperature of the interior must be very high. Suppose, for example, that the increase of temperature is only one degree for 100 feet. Then the increase of temperature at the depth of a mile would be 50 degrees. At the very moderate depth of 100 miles we should find a temperature of 5,000 degrees, which would not only liquefy but vaporize most substances. It has been inferred from this that the interior is in a molten state, which has been further proved by the expulsion of melted rock material from volcanoes, these having been interpreted as cracks through the solid crust covering the fluid interior.

In these conclusions regarding the condition of the interior of the earth a very important factor has been neglected. It was remarked above that the pressure at moderate depths in the earth is very high indeed. Now pressure tends to keep matter in a solid state in spite of high temperature. That is, if a temperature of 2,000 degrees will melt a substance at ordinary atmospheric pressure, a temperature of 3,000 degrees might be required to melt it if it were subject to a great pressure. While the combination of such extremely high pressures and temperatures as prevail in the interior of the earth have not been realized in experiments, still there is room for doubt as to the conclusion regarding the fluidity of the interior of the earth. The effects of pressure in retarding the melting are similar to those of raising the boiling points of liquids. At the sea level under ordinary atmospheric pressure, water boils at 212° F., but on the tops of high mountains where the pressure is perhaps 25 per cent less, the boiling point is considerably lower. This leads to the well-known fact that water boils away rapidly on the mountains, and that things to be cooked by boiling are cooked only with difficulty, the reason being that sufficiently high temperatures are not obtainable.

There are now definite reasons for believing that the earth is solid through and through, and one of them is that the earthquake waves are transmitted as they would be if it were a solid. The speed with which a wave travels through any medium, for example, the wave produced by striking a steel beam with a heavy hammer, depends upon the density of the medium and its rigidity. Earthquakes are similar waves in the earth. We now have very delicate instruments for measuring them, even at those remote distances from the seat of disturbance where they have become very small. Suppose an earthquake starts in Japan, where many of them do start, and that it is of such intensity that the waves can be detected when they reach Europe and America. We shall suppose the time of the earthquake in Japan has been recorded, and that the time the wave reached Europe and America has also been recorded. The distance and the time it has taken the wave to travel from one place to the other being known, it is possible to compute the speed of the wave. Now, as has just been stated, the speed depends upon the density and the rigidity of the medium through which the waves pass. In the case of the earth the density is known, as we have shown above. Consequently, the only unknown is the rigidity of the earth, which from these observations turns out to be, on the average, considering the earth through and through, about that of steel.

There are other methods of determining the rigidity of the earth, and they lead to the same results. One of them is the tides that the moon raises in the earth. It can be shown from a mathematical discussion of the question that if the earth had a thin crust, say 100 miles in depth, and a fluid interior, then this crust would yield under the tidal force so the water on its surface would not be heaped up in tides. It is clear that if the crust yielded there would be no reason for the water to flow along it under the tidal forces. Now, it is found by observations that the tides are the height they should be if the solid part of the earth had a very high degree of rigidity. That is, the tidal phenomena in connection with a difficult mathematical theory prove that the earth is rigid when considered in its entirety.

It was stated above that the moon's attraction on the equatorial bulge of the earth produced changes in its rotation. If the interior of the earth were fluid, so that the equatorial bulge could slip on the interior, then the attraction of the moon for it would produce more rapid changes in the motion of the interior of the earth than it would if the equatorial bulge were solidly attached to the whole earth so that the moon would have to move all of it. It is possible to compute the rate of change under the hypothesis that the earth is a solid and also under the hypothesis that the equatorial bulge can slip on the interior. It is found from the actual observations that the rate of change is just what it should be if the earth were solid through and through. The conclusion to be drawn from this line of reasoning is that the earth is not only solid but that it has a rigidity about equal to that of steel.

There are other indirect methods of treating the question and they all lead to the same conclusion. The fact that the earth is solid in the interior—when a more superficial examination of the question would lead to the conclusion that it is fluid—is of the highest interest. It is clear that this is a very important result for the geologist. It is interesting from the scientific point of view that we have been able to reach certain conclusions respecting portions of the earth which can never directly come under our observations. It is one of the triumphs of science that, through the application of laws which are discovered in treating material which is accessible to us, we can discover the properties of that which is inaccessible.

Composition of the Earth's Atmosphere. The atmosphere is the gaseous envelope which surrounds the earth. It is made up of nitrogen and oxygen and a few other substances. The thousands of substances which are found on and in the earth are made up of about eighty fundamental substances called *elements.* For example, water is a combination of the elements oxygen and hydrogen, and sugar is a more complicated combination of carbon, oxygen, and hydrogen.

Of the earth's atmosphere about 79 per cent is nitrogen, about 21 per cent is oxygen, and in addition there are very minute quantities of other elements such as argon, neon, and helium, and some compounds such as carbon dioxide and water vapor. Carbon dioxide is a compound made up of carbon and oxygen, and is produced by the combustion of coal, wood, and most other substances.

Height of the Earth's Atmosphere. It is found upon ascending mountains or going up in balloons that the density of the atmosphere steadily decreases with increasing altitude. Numerous observations in various places on the earth and at various times have shown that at a height of three and a half miles above the surface of the earth the density is approximately one-half that at the surface. It is also found from balloon ascensions that an ascent of three and a half miles more reaches a place where the density of the atmosphere is one-half of that at the three and a half mile level, or one fourth that at the surface of the earth. So far as it has been possible to extend the observations, the density of the atmosphere is divided by two for every three and a half miles of ascent. If this law were indefinitely continued the atmosphere would, of course, have infinite extent, though the density would become very low after a few miles. For example, the density at the height of 28 miles would be only $\frac{1}{256}$ that at the earth's surface.

It is not possible to determine by any means whatever exactly where the earth's atmosphere ceases. In discussing its height we can refer, therefore, only to the height to which it extends in sensible quantities. Clouds do not reach an altitude above 10 or 12 miles, and balloons have not been sent higher than that. Therefore, for the purpose of carrying water vapor and balloons we might say its height is approximately 12 miles. But there are other phenomena which do not require so dense an atmosphere for their existence.

A very good means of determining the height of the atmosphere is from the observations of meteors. These little flashes of light in the sky, which are commonly called shooting stars, are due to minute masses of matter, traveling in the interplanetary spaces, which are entirely invisible until they dash into the earth's atmosphere. They travel with very high speed, even as great as twenty or thirty miles per second, and the friction they encounter in striking the atmosphere generates so great a heat that they become luminous. As they are burned up and their motion is destroyed the incandescent particles associated with them cool off and they become invisible. Now, it is possible by direct observations to find the height at which meteors burn.

In Fig. 7, suppose there is an observer on the surface of the earth at *A* and another a few miles distant at *B*, and suppose a meteor strikes the atmosphere at *m*. The observer at *A* will see it at an angular elevation of *a* and the observer at *B* at an angular elevation of *b*. When these angles have been measured and the distance from *A* to *B* is known, it is possible to compute the height of *m* above the surface of the earth. The computation is made by trigonometry, but one can get fairly accurate results without the use of it. On drawing paper the distance *A* and *B* can be laid down to any convenient scale and the angles *a* and *b* laid off. The place where the lines intersect will be the point m. The distance from m to the line AB can be measured directly by a ruler, and it can be found in this way how the height of a meteor is related to the dis-

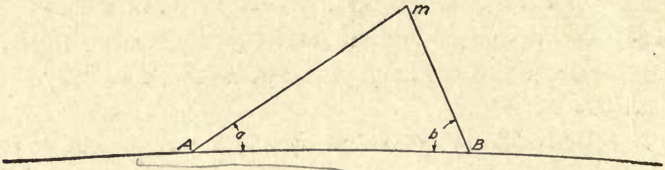


Fig. 7. The Height of the Meteor m Can Be Determined by Observations from A and B

tance of A from B. Many observations of this sort have shown us that the atmosphere is sufficiently dense to an altitude of about 100 miles to cause the meteors to burn when they strike into it. Nearly all of them are totally consumed before they reach an altitude of 50 miles.

Another phenomenon which depends upon the height of the atmosphere and by means of which we can compute its height is the twilight.

In Fig. 8, suppose the sun is very far to the left and shines toward the right, its rays striking the earth in sensibly parallel lines. For an observer at the point P the sun is on the horizon. Suppose,

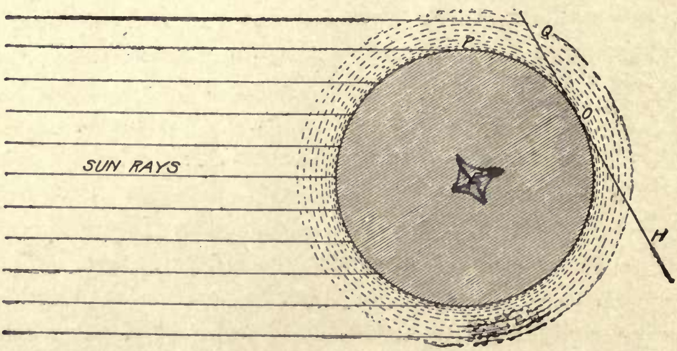


Fig. 8. An Observer at O Sees the Twilight at Q Until the Sun Is Far Below the Horizon. From the Duration of the Twilight the Height of the Atmosphere Can Be Found

for example, it is setting. For an observer at O the sun has been down some time, depending upon the distance from O to P. The horizon of the observer at O is indicated by the line H. Now, it is clear from the diagram that some of the atmosphere which is above H, viz, that at Q, is illuminated by the rays of the sun. Consequently, the observer at O, looking toward his western horizon, will see the atmosphere somewhat illuminated. It is also clear from the diagram that the length of time the illumination will be visible in the west depends upon the height of the atmosphere. The higher the atmosphere the longer it can be seen. Actual observation shows that the twilight lasts until the sun is 15 to 20 degrees below the horizon. When the matter is discussed mathematically this proves that the atmosphere is dense enough to an altitude of 40 to 60 miles to produce the twilight phenomena.

Another means of determining the height of the atmosphere is by the aurora, a phenomenon on which is now well understood to be an electrical display in the rare gases of the high upper atmosphere. Suppose a well-defined auroral streamer is observed from two places at the same time. Then, as in the case of computing the height of the meteor when it becomes visible, the height of the auroral streamer can be computed. Observations of this phenomenon have shown that the auroral light is visible to a height sometimes as great as 400 miles.

It is seen that the various methods of determining the height of the observer do not agree, and the reasons for their disagreement are plain. They are not in harmony because each one determines where the atmosphere ceases to be dense enough to produce the particular phenomenon in question. Speaking from a practical standpoint, we may say that sensibly all of the earth's atmosphere is within 100 miles of its surface.

In considering the mass of the earth one might at first think it is inappropriate to consider the atmosphere as a part of it, but upon a little reflection it is apparent that the atmosphere is as much a part of the earth as the water which covers a large part of its surface, or as the solid part itself. Taking into account the density and extent of the atmosphere, it is found that altogether it is about $\frac{1}{200000}$ that of the remainder of the earth.

Kinetic Theory of Gases. For certain discussions it is essential to have a clear idea of the nature of a gas. It has been stated above that the atmosphere is made up of a few elements and compounds in the gaseous state. These masses are composed of vast numbers of extremely small particles called *molecules.* In fact every substance, whether it is an element or a compound, is made up of small particles called molecules. When an object is in the solid state its molecules are fixed relatively to one another. If this were not so a solid body would not preserve its shape. While it is true that they are fixed to the extent that they do not move around among one another, they, nevertheless, have slight oscillatory motions.

In the case of a liquid the molecules not only oscillate but move around among one another. If two liquids of the same density but of different colors be put together it will be seen they gradually mix completely because of this fact. While the molecules move around among one another in the case of liquids, they, nevertheless, do not move freely because they are so close together that each one is continually subject to restraints from the neighboring ones.

In the case of a gas the molecules are far apart compared to their size, and they dart around in every direction with great speed. The collisions of the molecules are extremely frequent, but the time that one is sensibly influenced by another one is short relatively to the time between collisions. For example, if a molecule makes a million collisions in a second it might be that it would be sensibly disturbed at these collisions all together during only $\frac{1}{1000000}$ of a second. The distinction between a liquid and a gas is that in the liquid the molecules are continually subject to restraints from neighboring ones while in a gas they are most of the time free.

The atmosphere exerts a pressure of about 15 pounds per square inch at the sea level. This is made evident by exhausting the air from a reservoir when it will be broken unless it is very strong. This pressure is produced by the impact of countless molecules which strike every square inch millions and millions of times per second. The individual strokes are so small and they are so frequent that the pressure is sensibly continuous. From the density of the atmosphere and the amount of pressure which it exerts, it is possible to compute the average speed with which the individual molecules move. Thus, hydrogen molecules under atmospheric pressure and at the freezing point move on the average with a velocity of more than a mile a second. The average velocity increases with the increase of temperature, and also with the increase of pressure. There are many molecules moving with velocities greater than the average, and many with velocities less. Theoretically there is no limit to the velocities with which a few may move. The higher the velocity the fewer the molecules which will be moving with it.

Escape of Atmospheres. Suppose a body is projected up from the surface of the earth. The height to which it will rise depends upon the speed with which it is started. The greater the speed the higher it will rise, and there is a certain definite speed for which it will leave the earth permanently. It is found, by computation based upon the mathematical formulas belonging to the question, that if a body leaves the surface of the earth with a velocity greater than seven miles per second it will, except for the resistance of the atmosphere, leave the earth and never return.

Now, let us apply this idea to the molecules of the atmosphere itself. They are darting to and fro in every direction with high speeds, the velocities in some cases being as great as seven miles per second. If a molecule is near the upper limits of the atmosphere where the chances of collision are growing small, and if it darts out away from the earth with a velocity exceeding seven miles per second, it will, unless it strikes another molecule, leave the earth permanently. In this way the earth is probably losing, molecule by molecule, some of its atmosphere.

The velocities with which the molecules of the atmosphere move depend upon their individual weights. The lightest molecules we know are those of hydrogen which, as has been stated, at atmospheric pressure and at the freezing point move with a velocity greater than one mile per second. The molecules which our atmosphere is largely made of, viz, nitrogen and oxygen, are, respectively, 14 and 16 times heavier than hydrogen and move on the average with about one-fourth the velocity of hydrogen. This velocity is so far below the seven miles per second necessary for escape from the earth that it is clear there is no great danger of the atmosphere escaping rapidly. Nevertheless, there is indefinite time available for its escape and there might be a danger of its being seriously depleted in this manner.

Before drawing definitely the conclusion that the earth is losing its atmosphere and that it is continually becoming more tenuous, we should see whether there are not some ways in which it is being restored. One of the ways in which the earth's atmosphere is increased is by the escape of gases from the earth itself, particularly from volcanoes and hot springs. But perhaps the escape of gases from the rocks as they are dissolved by the action of the water and air is equally important, for it is found that almost all the rocks of the earth's surface contain in their interstices large quantities of gas, which is called *occluded* gas.

There is another way in which the earth's atmosphere is probably to some extent replenished. It was remarked above that meteors strike into the earth's atmosphere and are burned up by friction with it. When a body is burned up the material of which it is composed is not utterly destroyed but is only changed in form. For example, when wood is burned the carbon in it unites with the oxygen of the air and produces carbon dioxide, which goes off as a gas. Some of the mineral substances remain behind in the ashes. The vapors given off in the process of combustion and the ashes left behind together equal the total quantity of matter in the original wood plus the oxygen added to it during the combustion. Therefore, when meteors strike into our atmosphere and are burned, the product of the combustion is added to the earth. If it is solid it slowly settles to the earth, and if it is gaseous it becomes a part of the atmosphere. The amount of atmosphere added in this manner in a year is, of course, small, but it may be sufficient to make up for that which is lost.

It is probable, also, that the region in the neighborhood of the sun through which the earth moves is filled sparsely with wandering molecules. They may have been lost from the earth and other planets, or may never yet have been gathered into any large body. If this is true the earth in its course around the sun would gradually gather them up and in this manner replenish its atmosphere.

It is clear from what has been said that there are ways in which the earth loses its atmosphere and others in which it tends to gain one. There is no astronomical means of determining whether the loss is greater than the gain or not. Probably the gain and loss have reached a state of equilibrium. If the earth had a very extensive atmosphere, so that its borders were farther from its surface it would lose it more easily and consequently more rapidly, while it would gain only a little more than now. If it ever had so large an atmosphere that it was lost faster than it was restored, probably enough of it has been lost so that it is now in approximate equilibrium. It is somewhat analogous to the condition of a body of water subject to evaporation. An exposed vessel of water continually loses particles by their leaping into the atmosphere. It also continually gains them by those which are in the atmosphere plunging into it. If the atmosphere is initially very dry, then the evaporation is more rapid than the restoration of water from the air. But as evaporation goes on, if the atmosphere above the vessel of water is enclosed, after a time a state of equilibrium is reached in which the loss and gain are exactly equal. Probably in a somewhat analogous fashion the condition of the earth's atmosphere, respecting its loss into space and the gain from the various possible sources, has reached a state of equilibrium.

It was stated above that in order for a molecule to escape from the earth it must leave its surface with a velocity of approximately seven miles per second. If the earth were smaller or less dense it would have a smaller gravitative power and a molecule could escape by leaving at a somewhat lesser velocity. The moon is an example of a smaller world where it is easier for molecules to escape. The diameter of the moon is about one-fourth that of the earth and its mass about one-eightieth. If a body leaves its surface with a speed of 1.5 miles per second it will permanently escape. It is a significant fact in this connection that the moon has no sensible atmosphere.

On the other hand, bodies which are larger than the earth have greater gravitative power and higher velocities of escape. In the case of the great planet Jupiter, which is nearly 1,000 times as big as the earth and has a mass more than 300 times as great, a body must leave its surface with a velocity of over 37 miles per second in order to escape. It is clear from this that it can control a much greater atmosphere than the earth can; and this theory is in harmony with the observed fact that Jupiter has a great atmosphere. In the solar system the greatest body is the sun, and the computation shows that a particle must leave its surface at the rate of 380 miles per second in order to permanently escape. Obviously, there is small chance for the particles of an atmosphere to escape from its control, and observation shows that it has a greater atmosphere than any other member of our system.

Effects of Atmosphere on Climate. Aside from the sun the atmosphere is the most important influence affecting our climate.

In the daytime, when the earth is subject to the direct rays of the sun, the atmosphere absorbs a considerable part of them and keeps the temperature from rising to the point it would otherwise reach. It is difficult to determine what part of the sun's radiation is absorbed in the atmosphere, but certain computations make it as high as 50 per cent. The effectiveness of the atmosphere in absorbing the sun's heat is noticed when one ascends a high mountain or even lives on an elevated plateau. In those exposed places the sun's radiation is noticeably more intense than at the lower levels. Therefore, one effect of the atmosphere is to keep down the temperature during the middle of the day. If the atmosphere absorbs a certain amount of the light and heat coming from the sun, it is not entirely lost to the surface of the earth because the atmosphere later radiates this heat again. Part of it is radiated out into space and part of it toward the earth. That is, some of the heat which comes from the sun is caught in the earth's atmosphere in the daytime and held there a while and delivered to the earth's surface by radiation at night. In this way the earth's atmosphere makes the surface of the earth warmer at night than it would otherwise be.

Another effect of the atmosphere is that it prevents radiation from the surface of the earth at night. Though the rays are not visible the earth radiates heat out into space as a luminous body radiates light. The atmosphere above the surface of the earth catches a part of this radiated heat and in turn radiates it again. A part of it, of course, comes back to the earth. It is a matter of common observation that the nights are very cool in the high altitudes, and the explanation is simply that the atmosphere there is so tenuous that it does not catch the heat which the earth is radiating. Therefore, considering the 24 hours, it is seen that the effect of the atmosphere is to reduce the variations in temperature.

There is another important way in which the atmosphere tends to equalize temperatures. The equatorial part of the earth receives much more light and heat than the high latitudes and this sets up great currents in the atmosphere. In the northern hemisphere the atmospheric currents are on the whole from the southwest toward the northeast. The point is that the atmosphere moves from the heated equatorial regions toward the frozen regions of the north. In this manner enormous quantities of heat are carried from regions where they are not needed to regions where otherwise it would be very cold. The effects are seen on the western coasts of the large land areas in the northern hemisphere, which in all instances have much warmer climates than corresponding latitudes on the eastern shores. It is clearly not because the western shores receive more heat from the sun, but because they are warmed by heat which fell on the earth elsewhere. Now, it is impossible for the atmosphere to go northward in the northern hemisphere without an equal amount going southward. The warm currents pass along the surface of the earth carrying the mild temperature into higher latitudes, and the cool air from the polar regions goes southward and reduces the temperature in the equatorial zone. In this manner the temperature at the surface of the earth considered as a whole is much more uniform than it would be except for the atmosphere.

The effects of the atmosphere on the climate depend to some extent upon its constitution. This is clearly seen to be so by considering the difference in temperatures when it is clear and cloudy. The gardener does not fear a frost on a cloudy night because he knows the clouds keep in the radiations from the earth and prevent the temperature sinking below the freezing point. On the other hand, when the atmosphere is clear and relatively free from water vapor it is more transparent to the radiations from the earth and the temperature falls more quickly and to a lower point.

Water vapor is not the only substance of the atmosphere which has the property of strongly absorbing light and heat. Another compound which is important in this respect is carbon dioxide. Though the amount of this substance is small in the earth's atmosphere it is probably important in absorbing the solar radiation. If the amount were considerably increased the mean temperature of the earth would rise, and if it were considerably decreased it would fall. This is an interesting point in connection with the fact which geologists have worked out for us, namely, that the climate of the earth has alternately been much warmer and colder than it is at the present time. The northern part of the United States has time after time been visited by great ice sheets which have pushed down from the North, and which show that at certain epochs the mean temperature has been much lower than it is at present. On the other hand, in intervening epochs the temperature has been higher, for in these altitudes and even so far north as Greenland semi-tropical plants have flourished. It may be that these oscillations in temperature are not due at all to astronomical causes but only to the varying composition of the earth's atmosphere. There are reasons for believing that for long periods the amount of carbon dioxide will decrease as it becomes locked up in coal beds and absorbed by the oceans, and that then for long periods it will increase. This change may be sufficient to cause all the climatic changes of which we have evidence. It is generally supposed that at the present time the amount of carbon dioxide in the atmosphere is slowly increasing and that the climate is getting slightly warmer. It should not be understood, however, that the change is rapid enough so that it can be observed for so short a time as a thousand years. Those changes which are observed, or which are supposed to have been observed, are almost certainly of a local and more temporary character.

It follows from this discussion that if one is to consider the question of the habitability of another world, the question of the extent and nature of its atmosphere is a very important one. In the first place, a definite constitution of the atmosphere is necessary for most of such life processes as take place upon the earth, and in the second place the climatic effects are so important that they may be the determining factor.

Refraction of Light by the Atmosphere. If light passes obliquely from a rarer medium into a denser medium, its direction changes slightly at the surface separating the two, the amount of change depending upon the differences of densities and to some extent upon the constitution of the two media. When the light from a celestial object enters our atmosphere from vacant space its direction is somewhat changed. In this case it does not pass from one medium into another of constant density, but as it passes down through our atmosphere it gets into a medium whose density continuously increases. Consequently, the path of the ray of light continually changes.

In Fig. 9, suppose the ray of light comes from a star S and strikes the atmosphere at the point A. At this point its direction begins to change and continually changes until it reaches the surface of the earth at O. An observer at O sees the star in the direction from which the light came when it entered his eye; that is, the star seems to him to be at S'. Since the star is at a distance which is sensibly infinite it is actually in the direction *OL*. Of course, in the diagram the difference in direction is greatly exaggerated. The point to be noticed is that the star appears to be higher in the sky than it actually is.

This change of direction, or atmospheric refraction, is zero for a star at the zenith, and increases continuously until the horizon is reached. At the horizon it is a little over one-half a degree, the exact amount depending upon several factors such as the density of the air at the time, *i. e.*, the barometric pressure, the temperature, and upon the amount of water vapor it contains.

One of the consequences of the refraction of light is that an object (for example, the sun) apparently rises before it actually is above the horizon, and apparently does not set until after it is actually below the horizon. That is, the sun is apparently above the horizon longer than it would be except for the refraction. One might infer

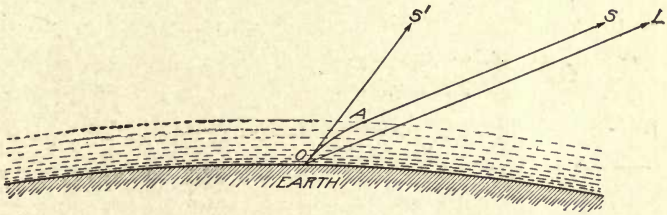


Fig. 9. The Light from the Star *S* Is Bent as It Comes through the Earth's Atmosphere so That It Seems to Be in the Direction *S'*

from this that we get more light and heat from the sun than we would if it were not for the atmosphere. But the absorption by the atmosphere of the sun's light and heat more than offsets this slight gain.

There is another interesting consequence of the fact that the refraction increases to the horizon. When the sun or moon is on the horizon, light from the upper part is refracted less than the light from the lower part. The lower part being apparently lifted more than the higher part makes it appear flattened in the vertical direction, as illustrated in the case of the sun, Fig. 10. This is often enough to be very conspicuous, and if it has not been observed it should be looked for.

In making astronomical observations it is often important to locate the exact position of the object. Now, it has just been seen that the apparent position is different from the exact position on account of refraction. Consequently, it is necessary to make corrections to the direct observations for this refraction. An example of where this is important is in making observations at sea for determining the position of a ship. The correction would be rather simple if it were not for the fact that the refraction varies with the state of the atmosphere. This introduces uncertainties which are important when the object under observation is near the horizon. In the most exact kind of astronomical work it is important that the observation should be taken when the object viewed is not far from the zenith, and this condition is always secured if possible.

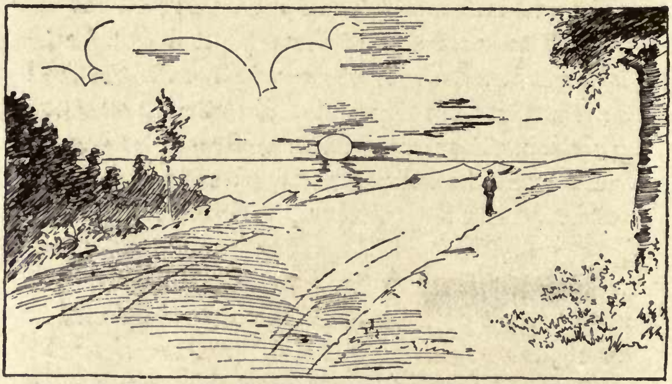


Fig. 10. The Refraction of Light Makes the Sun Appear Flattened When It Is Seen on the Horizon

The atmosphere is not only of variable density from the highest regions to the surface of the earth, but there are waves in it which cause the density at a given point continually to vary. This makes constant changes in the refraction of light, though, of course, of no great extent. One of the consequences of this varying refraction is seen best in observations of the stars. On a clear night, especially in the winter time, and particularly if it is not calm, the stars are seen to twinkle or scintillate. This twinkling is due entirely to the fact that the light from the stars is passing through an atmosphere whose density is constantly changing so that the refraction is unsteady. It is easy to verify the fact that the twinkling is greater the nearer the star is to the horizon.

Relative Rotation of the Earth. The most casual observer of the heavenly bodies knows that the stars rise in the east, pass across the sky, and set in the west, just as the sun and moon do. This refers to those which are not near the pole of the sky. Any observer of the stars can see that those which are near the pole of the sky go around it in circles whose centers are very close to the pole star. For example, if the Big Dipper is on the east side of the pole in the evening it will pass in a circle around above it during the night and be on the west side in the morning. If one knows where it is in the evening he can tell the time of night, at least approximately, by observing its position.

Fig. 11. Circumpolar Star Trails Photographed at the Yerkes Observatory

Fig. 11 shows the trails of the stars in the vicinity of the pole as they were photographed during an exposure of a little more than an hour with the telescope pointed to the northern sky and kept fixed. The conspicuous streak below the center and a little to the left is the trail of the pole star itself, which is thus shown to be not exactly at the pole of the sky. Most of the stars whose trails are shown are invisible to the unaided eye.

Since all heavenly bodies rise in the east (except those so near the pole they simply go round it), travel across the sky, and set in the west to reappear again in the east, it follows that either they go around the earth from east to west or the earth turns from west to east. So far as these simple observations go it is not possible to determine which of the two theories is correct. It is incorrect to suppose that those ancients who believed that the earth is fixed and the sky goes around it adopted any theory which violates the common facts of observation. This theory is as much in harmony with the apparent motions of the heavenly bodies as the one we have, viz, that the stars are fixed and that the earth turns from west to east. It has already been remarked that one of the characteristics of science is that it gives reasons for its conclusions. Therefore, it will be necessary to take up and explain the reasons we have for believing that the earth moves and that the sky is fixed. Before taking up the question of the motions of the earth in particular, we shall consider the laws of motion of bodies in general.

Laws of Motion. The laws of nature are in an important respect different from civil laws, and it is to some extent unfortunate that the same term is used. A civil law prescribes a mode of conduct and penalties if it is violated. A civil law can be broken at will if one is willing to accept the penalty, or at least the chance of it. A natural law, or a law of nature, on the other hand, does not prescribe anything, but is a statement of the way all phenomena of a certain class proceed. If it is a true law of nature it describes the way phenomena invariably proceed and there are no exceptions to it.

The laws of motion are statements of the way bodies actually move. They were first given in their completeness by Newton in the *Principia* in 1686, although they were to some extent understood by his predecessor Galileo. They were called by Newton *axioms*, although they can hardly be said to be axioms in the ordinary sense of the term, since for thousands of years men believed motions were different from what they are as expressed by these laws. The laws, essentially as Newton gave them, are:

LAW I. *Every body continues in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by exterior forces acting upon it.*

Law II. *The rate of change of motion is proportional to the force impressed and the change takes place in the direction of the straight line in which the force acts.*

Law III. *To every action there is an equal and opposite reaction; or, mutual actions of bodies are always equal and oppositely directed.*

The importance of these laws can be understood from the fact that every astronomical phenomenon involving the motion of matter, and everything upon the earth involving the motion of matter, is interpreted by using them as a basis. A little reflection will show that there are few things, indeed, which are not associated with the motion of matter. Even the process of thinking is probably associated with the motion of matter in the changing structure of the brain. Because of the wide application of these laws it is necessary to give them careful attention.

The first law states the important fact that if a body is at rest it will never begin to move unless some force acts upon it, and if it is in motion it will forever move at uniform speed in a straight line unless some exterior force acts upon it. This in two respects is opposite to the views held generally before the time of Newton. In the first place, it was supposed that bodies would descend without forces acting upon them. In the second place, it was supposed that if a body were in motion it would stop unless some force were continually applied to keep it going. These errors prevented the predecessors of Newton getting any satisfactory explanation of the motions of the heavenly bodies.

The second law means by the "rate of change of motion" the product of the mass and the rate of change of velocity. It might be made to read, the rate of change of velocity is proportional to the force impressed and inversely proportional to the mass moved, and the change takes place in the direction of the straight line in which the force acts. The first two laws consider a single body subject to exterior forces.

The third law expresses the way in which two bodies act on each other. It means essentially that no body can change the state of the motion of another body without having its own motion correspondingly changed, and this is equally true whether the bodies are in actual contact or connected by some invisible bond of force such as gravitation. The difficulties in getting a clear mental picture of this law come largely from the fact that it is not possible to get two bodies subject only to their mutual interactions. If a man and a small boy pull in opposite directions on a rope, the man pulls the boy, and it seems that the law is violated. The reason of the apparent violation of it is due to the fact that there are other forces in operation, particularly the friction of the feet of the man and the boy with the ground. If they were both in small boats on the water, then each would move with a speed inversely proportional to his mass. It follows from this fact, which we shall suppose is verified in experiment, and the second law of motion, that the forces are equal and opposite. The more nearly the exterior forces are eliminated the more nearly the law is verified. It is to be understood that the laws of motion can be verified with a high degree of precision in the laboratory. They have been tested in this manner thousands of times and no deviations from them have been observed that can not be explained by extraneous forces which it was not possible to eliminate. They have also been verified indirectly in thousands of ways, and some of these verifications, particularly in astronomy, are more exact than any of a direct character. Just as railway trains obey the laws of motion and in consequence would jump the track on curves if the outside rails were not elevated, so also the heavenly bodies in their motions obey the laws. But in the case of heavenly bodies the disturbing factors are almost entirely absent, and the operation of the laws is observed under almost ideal conditions.

Rotation of the Earth Proved by Eastward Deviation of Falling Bodies. If the earth rotates, then the farther a body is from its axis the faster it goes. The circumference of the earth at the equator is about 25,000 miles, so that a body on the surface of the earth at the equator moves eastward if the earth rotates at the rate of about 1,000 miles an hour.

In Fig. 12, suppose that C is a point on the axis of the earth and that CP is a line perpendicular to it. Suppose O is the top of a high tower whose base is at P (of course, the height of the tower is greatly exaggerated in the figure), and suppose the earth rotates in the direction PP' and that the line CP moves to CP' in one unit of time. Therefore, a mass at the bottom of the tower has the velocity PP'. Now, consider a body at the top of the tower O whose velocity is OO'. When the body is dropped its motion will be the resultant of its motion toward O' and of the attraction of the earth for it toward C. This attraction is at right angles to the line OO' and will, therefore, *not diminish the velocity in this direction.* Hence, in the unit of time the body will move precisely as far eastward as though it were not falling. Since the earth's attraction acts continuously it will fall faster and faster until it strikes the surface of the earth. The curve described by the body will be OQ, Q being the point where it strikes the earth. This point will be east of the foot of the tower P' at the time it strikes the surface because the distance OO' is greater than PP'. Therefore, the falling body will have an eastward deviation. On the other hand, if the earth were not rotating it would strike at the foot of the tower.

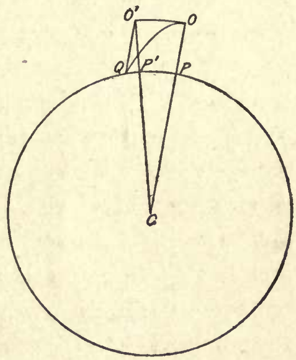


Fig. 12. The Eastward Deviation of Falling Bodies Proves the Rotation of the Earth

From this discussion we see how the body will fall if the earth rotates and how it will fall if it does not. The experiment will decide the matter. The problem is one of some practical difficulty because very slight air currents will cause enough change in motion to mask the small eastward deviation, which in our latitude amounts to only about an inch in a fall of five hundred feet. The most successful experiments have been carried out in mine shafts where large falls can be secured and where by covering them the air currents can be destroyed. The experiments have actually shown the eastward deviation, and therefore have proved the eastward rotation of the earth.

Rotation of the Earth Proved by Its Shape. It follows from the laws of motion stated above, and the law of gravitation, that if the earth does not rotate it will be exactly spherical except for slight irregularities due to its lack of homogeneity. It also follows from the laws of motion that if it is rotating it will be bulged at the equator and flattened at the poles. The first law of motion asserts that a body subject to no forces will move in a straight line. Now, the particles at the earth's surface, especially at the equator, tend to move in a straight line in harmony with this law, and are held to the earth only by its attraction. This tendency to move out in straight lines produces the equatorial bulge. If the earth moved seventeen times as fast as it does now and were of the same size and shape, a loose particle on its surface at the equator would fly away into space.

It is seen that if the earth did not rotate it would be round, and that if it did rotate it would be oblate. The observations again must settle the question as to which is true. As was explained above, measurements of arcs on the surface of the earth have shown conclusively that the earth is bulged at the equator and flattened at the poles. Therefore, we are forced to the conclusion that the earth rotates. This method of proving its rotation gives us the position of its axis but does not determine for us which way it moves.

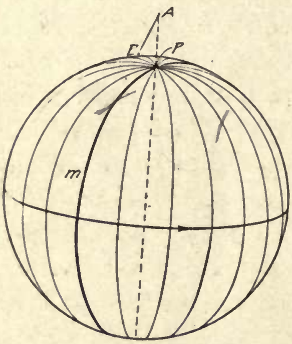


Fig. 13. Proof of Earth's Rotation by Foucault Pendulum

Rotation of the Earth Proved by Foucault's Pendulum Experiment. It follows from the laws of motion that a pendulum set swinging tends to move continually in the same plane. Let us imagine a pendulum suspended from *A*, Fig. 13, over the exact pole of the earth, and suppose that it is started swinging in the plane of the meridian *m*. If it is subject to no other force than the attraction of the earth, which is directed toward the earth's center, it will continually swing in this plane. Let us suppose that the earth is rotating toward the east, the direction being indicated by the arrow on the equator in Fig. 13. The meridian *m* will turn in the direction of the arrow while the pendulum stays fixed. If an observer were on the earth at the pole the earth would, of course, seem to him fixed as it does to us where we live, but the pendulum would seem to him to be turning in the westward direction. If he should watch it for 24 hours he would find that it made a complete apparent revolution in that time.

If the pendulum were suspended at the equator instead of at the pole there would be no more tendency for it to rotate in one direction than the other, and, as can be easily seen, it would not change the apparent plane of its vibration. Therefore, an observer there would notice no rotation of the pendulum.

Now, consider a point between the pole and the equator. At the pole the plane of the pendulum's motion rotates in 24 hours and at the equator it does not rotate at all. In the intermediate latitude it rotates but the period is longer than 24 hours, its length depending upon the latitude. In our latitude the period of apparent rotation is about 36 hours.

It follows from this discussion that if a pendulum is set swinging in our latitude, the plane of it apparently slowly deviates to the west if the earth rotates to the east. On the other hand, if the earth is fixed, it will continually swing in the same plane. The experiment must be made in order to prove which theory is correct. This very ingenious and convincing method of proving the rotation of the earth was devised and carried out by Foucault, in Paris, in 1851. He suspended a heavy iron ball by a steel wire about 200 feet in length. It was pulled to one side of its lowest point and fastened by a thread and left until it came perfectly to rest. Then the thread was burned so as not to give it any sidewise disturbance, and it began to swing. Underneath it the floor was marked so that the direction of its swing could be seen easily. It was observed then that hour after hour it apparently deviated to the west, which meant, of course, that the earth was turning to the east under it. This experiment can be easily performed in space where a shaft of considerable length, free from disturbances, can be secured. In carrying out the experiment it is necessary to be careful to start the pendulum swinging in an exact plane, for if it has a slight elliptical motion it will perform a rotation independent of that produced by the actual motion of the earth. Since this experiment has been many times performed and has always shown a westward apparent deviation in harmony with the theory, we must conclude also from this line of evidence that the earth rotates eastward.

Analogy with Other Heavenly Bodies. It is found from observations which do not depend upon the theory that the earth rotates or does not rotate, that many of the other heavenly bodies are comparable to the earth in size. The moon and some of the planets are smaller; Venus is about the size of the earth; Jupiter is about one thousand times greater; and the sun about a million times greater. Our modern powerful telescopes show markings on many of these objects of such a character that it can be determined whether they rotate or not. It is found that all of them on which markings can be observed turn on their axes, and what is a remarkable fact, in the same direction. The periods of their rotation vary considerably. For example, that of the moon is $27\frac{1}{4}$ days, Jupiter about 10 hours, and the sun about 25 days. But the essential point of interest here is that these other bodies, which are in most essential respects similar to the earth, some being smaller and some larger, all rotate. It is not reasonable, therefore, to suppose that the earth is the one exception. Hence, we should conclude from this alone that the earth does rotate, though this proof is by no means so conclusive as the proofs given above.

Uniformity of the Earth's Rotation. It follows from the laws of motion, and in particular from the first law, that if the earth were subject to no external forces and were fixed in size and shape, it would rotate on its axis with absolute uniformity. One might suppose the matter could be tested by comparing it with clocks. But as a matter of fact all the clocks which have been made, and which probably can be made, run with so much greater irregularity than the earth rotates that no test of this character can succeed. In fact, the rotation of the earth is used to check the running of clocks and to regulate them when they depart from perfect adjustment.

One might test the rotation of the earth by comparing it with some other celestial phenomenon which is known to proceed uniformly. There are, however, no such phenomena. Probably the earth is as good a measurer of time as anything which can be observed. The best we can do is to discuss those forces and changes which have a tendency to change its rate of rotation.

The earth is rotating in the luminous ether and a considerable quantity of meteoric matter. The latter, if not the former, has a tendency to retard its rotation and consequently to make the day a little longer. But this resistance is exceedingly small and certainly does not lengthen the day by a second in 1,000,000 years.

The moon and sun generate tides in the earth which on the whole move around it in a westerly direction, because these bodies in their apparent motions move to the westward. The tides, therefore, on the whole, beat in upon the eastern shores and act as a break on the rotation of the earth. While there can be no doubt whatever that the tides slow up the rotation of the earth to some extent, the amount of the retardation is probably so small as to be of no importance whatever. It is not possible to measure it with any degree of exactness, but it is not likely that the earth's day increases in length from this cause one second in 500,000 years.

The interior of the earth is hot and it is gradually losing heat by conduction to the surface and radiation into space. As it loses heat it probably shrinks a little. If a rotating body shrinks it rotates faster. The principle upon which this statement is based, which is a conclusion drawn from the laws of motion, is that in a rotating body subject to no exterior forces the whole quantity of rotation is a constant. By quantity of rotation is meant the mass multiplied by the velocity multiplied by the distance from the axis of rotation. Therefore, if a body shrinks so that the distance of each mass in it from the axis of rotation becomes less, the velocity must be increased in order to restore the equality. Theoretically this effect would lead to a shortening of the day. But the earth's contraction, because of heat losses, is so slow that probably the length of the day is not diminished in this way by so much as one second in twenty million years.

There are certain other causes besides its shrinking which change the distance of matter from its axis of rotation. For example, if a river runs from high latitudes to low latitudes, as the Mississippi, and if it carries sediment in its waters and deposits it in low latitudes, by this process matter is taken from a certain distance from the earth's axis and left at a greater distance from it. So far as this factor is concerned, the earth is to some extent retarded in its rotation. Not all rivers, however, run toward the equator and those flowing in the opposite direction offset this. The evaporation of water in equatorial regions and its deposit as snow in the higher latitudes is a factor working in the other direction and there are, also, many relatively minute surface changes, some acting one way and some another.

Some of the causes which have been enumerated above tend to increase the rate of rotation and others to decrease it. It is not possible to determine at the present time whether, on the whole, the day is becoming longer or shorter. The only thing certain about it is that the rate of change is exceedingly slow and will not produce sensible results before millions of years have elapsed. This is a question of some practical interest because if the day should become very much longer, say forty hours in length, the temperature in our latitudes would fall so low nearly every night in the year that there would be killing frosts. Again, in the correspondingly longer day the temperature would rise higher than under present conditions.

Variation of Latitude. In the preceding paragraph the discussion referred to the possible change of the rate of rotation of the

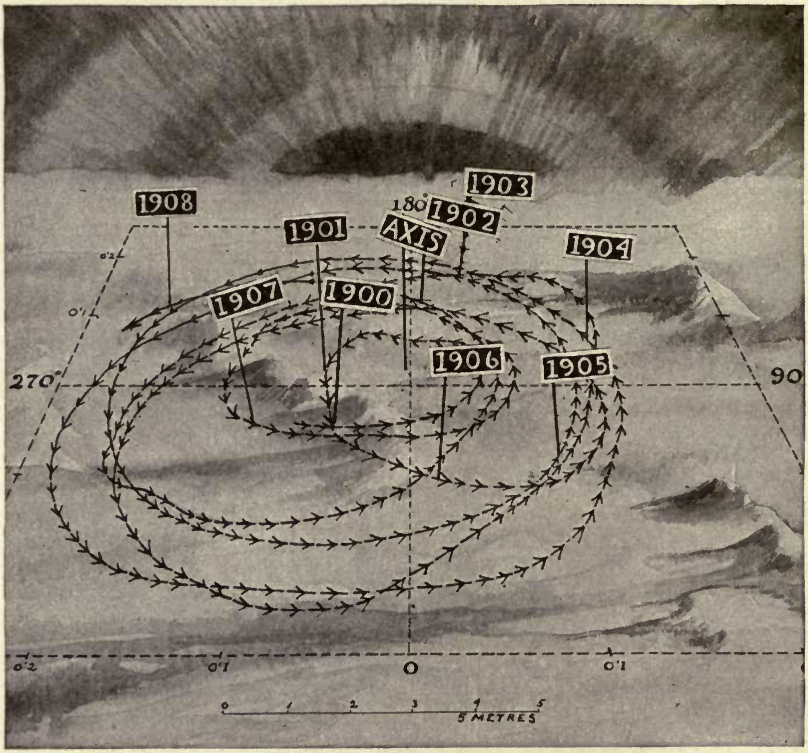


Fig. 14. The Path of the Earth's Pole from 1900 to 1908

earth on its axis. The question before us now is whether the earth continually rotates around some fixed axis. It has sometimes been supposed by those not familiar with the dynamics of the question that the former warm temperatures in the high latitudes and the cold temperatures in the low latitudes might be accounted for by a change in the position of the axis of the earth. It is not dynamically impossible that the axis of rotation should change, but if it does change it would be in the nature of an oscillation around some mean position. That is, the earth might have a sort of wabbling motion, just as a top has when it is not running steadily. Observations made for the purpose of detecting wabbling did not succeed until about thirty years ago. The reason of the failure was that the amount of deviation was exceedingly minute. This wabbling is spoken of as the variation of latitude, or the variation of the position of the pole, the movements covering a territory about 60 feet in diameter, Fig. 14.

If a top is running so steadily that it "sleeps" it will run permanently in that condition unless disturbed by some exterior force. As a matter of fact, there are many exterior forces always operating on the top. Similarly, if the earth were rotating around the axis of its figure it would forever run that way unless it were disturbed by external forces, or by some redistribution of its own mass. As has been stated, there is a slight wabbling and the question at once arises as to what are the causes which have produced it. At the present time they are not known. There are many things which have some influence upon it, such as the varying wind and ocean currents during the year, and the deposition of snow in the high latitudes. Also the attractions of the moon and sun on the equatorial bulge may have some effect.

The nature of the causes is indicated to some extent by the character of the wabbling. If the earth were not disturbed it would wabble in a perfectly definite fashion, depending upon its mass, size, shape, and rate of rotation, and would forever continue to wabble in this fashion if it were perfectly rigid. The period of this wabbling is also a perfectly definite quantity. The observations have shown that the wabbling is of a complicated character, being really the result of two separate motions. One has a period of one year, and the other of about 430 days. The yearly period is not the natural one for the earth's wabbling and consequently this irregularity must be produced by a continually acting force whose period of change is one year. The other irregularity is that one which the earth would have if it were left entirely free from external disturbances. Now, 430 days is not the period the earth's wabbling would have if it were absolutely rigid. If it were a perfect solid, yielding to no forces however great, its period of wabbling would be about 305 days. But if its rigidity were only that of steel, which must be considered highly elastic in treating of so great a mass as the earth, then its period of wabbling would be about 440 days, which is near that actually observed. It follows from this that the rigidity of the earth is between that of the perfectly unyielding solid and that of steel, and that it is near that of steel. Therefore, we have here a new proof that the rigidity of the earth, when considered through and through, is about that of steel.

Apparent Motion of the Sun with Respect to the Stars. The rising and the setting of the sun are such conspicuous phenomena that the most careless observer understands them well. But it is not so well known that the sun has a motion among the stars. It moves eastward about as the moon does, only less rapidly. Nearly everyone has noticed the fact that the moon moves day by day eastward among the stars. The reason the phenomenon is not noticed in the case of the sun is that the stars can not be seen in its immediate vicinity. But indirectly, the fact can be easily established and was well known in remote antiquity.

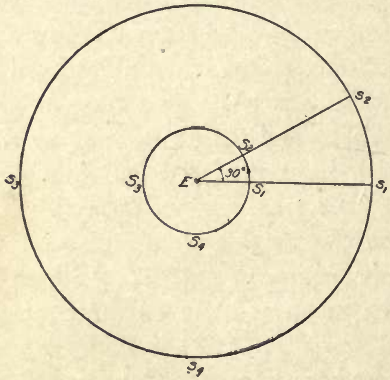


Fig. 15. The Sun Would Have an Apparent Eastward Motion If the Earth Were Fixed with the Sun Moving Around It

Suppose a certain group of stars is on the meridian at midnight when the sun is exactly opposite. That is, if one starts at the sun and goes eastward along the sky until he gets to the stars he finds them at a distance of 180 degrees. Suppose that after a month the same group of stars is found 30 degrees west of the meridian at midnight. In this case, starting from the sun and going eastward along the sky to the stars, he has to go a distance of 180° − 30°, or 150°. Since it is now 150 degrees from the sun to these stars, while a month before it was 180 degrees, it means that the sun has gone eastward among them 30 degrees. Just such facts as these are actually established by the observations. Every month in the year the sun goes eastward among the stars 30 degrees. It can be indirectly established, as has just been explained, and more directly by the use of large telescopes which will show the brightest stars fairly close to the sun. Hence the question of the explanation of this phenomenon arises.

In Fig. 15, suppose E represents the earth which is fixed except for its rotation which was proved above. Suppose the sun moves around the earth in the curve $S_1S_2S_3S_4$. When it is at the point S_1 it is opposite the stars at s_3 and in the direction of the stars at s_1. The stars at s_3 are visible on the meridian at midnight and those at s_1 can be seen only with a telescope. Counting in the direction of motion from s_1 to s_3 the distance is found to be 180 degrees. In a month suppose the sun is at S_2. Then the stars at s_3 are 30 degrees west of the meridian at midnight and those at s_2 are in the direction of the sun and can be seen only with a telescope. Now, the distance from s_2 forward in the direction of the sun's motion to s_3 is 150 degrees. As the sun proceeds around the earth it is successively seen in all directions from the earth. This is in perfect harmony with the facts of observation as recorded above. Consequently, it is easy to see why the ancients were satisfied with the theory that the earth is the center of the universe, since they had only those observations which we have mentioned, and which have just been shown to be in harmony with this theory.

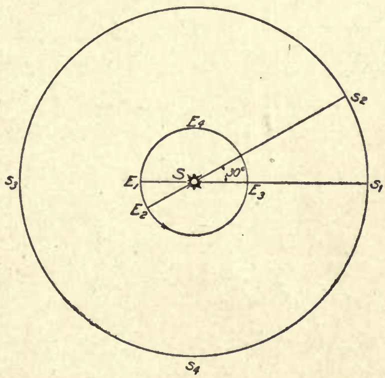


Fig. 16. The Motion of the Earth around the Sun Causes It Apparently to Move Eastward among the Stars

Now, suppose S, in Fig. 16, represents the sun, and that the earth moves around it in the curve $E_1E_2E_3E_4$. When the earth is at E_1 the sun is in the direction of the stars at s_1. Suppose the earth moves forward in its orbit to E_2 in one month. The sun then appears to be among the stars at s_2, and as the earth moves forward in its orbit the sun apparently moves forward among the stars and completes a circuit of the heavens, while the earth goes around the sun. It is seen that the *apparent* motion of the sun in this case is exactly the same as that when the earth was supposed to be fixed at the center and the sun to go around it. This theory is therefore in as perfect harmony with the ordinary observations of the apparent motion of the sun as the preceding, and the ancients might have adopted it as well as the other. As a matter of fact, the *heliocentric theory,* as this is called, was advanced by the ancient Greeks. However, it is clear from this discussion that the facts furnished by observations of the apparent motion of the sun are not sufficient to enable us to decide which of the two theories is the correct one.

The proofs that the sun is the center and that the earth revolves around it will be gone into with some care. This was a subject of bitter discussion for many centuries, but the matter was settled three hundred years ago in the days of Copernicus and Galileo, and has been open to no question whatever since the time of Newton. The first modern astronomer to develop definitely the heliocentric theory and to attempt to work out the motions of the heavenly bodies and in particular the sun upon it, was Copernicus (1473-1543). It is to be understood that not only is the motion of the sun to be explained, but the motion of the planets with respect to it, and this complicates the question greatly. Copernicus succeeded in showing that the heliocentric theory is in harmony with all the observed motions of his time, and he drew the conclusion that this is the correct theory since it is more reasonable than that the relatively small earth is the center for the motions of all the great bodies, especially for that of the sun. He did not have what we would now regard as a strict proof of the correctness of this theory.

Revolution of the Earth Proved by the Parallax of the Stars. Let us suppose that the stars are fixed objects in the heavens. Then, if the earth is the center and the sun goes around it, they will always appear in absolutely the same directions. On the other hand, if the sun is the center and the earth revolves around it, they will appear in slightly different directions at different times of the year.

In Fig. 17 let S represent the sun and AB the orbit of the earth. Suppose s is one of the fixed stars. When the earth is at A this star will be seen in the direction As; six months later when the earth is at B it will be seen in the direction Bs. Every star will be slightly displaced in this fashion because of the earth's motion around the sun. This difference in direction of a star, as seen at two different times of the year, is called its *parallax.* Consequently, in order to determine whether the earth is fixed or moves around the sun, it is only necessary to observe whether the directions of the stars are absolutely fixed or not.

It is clear from the figure that the farther the star is away the smaller will be its change in direction as seen from the two points *A* and *B*. It is analogous to the fact that if one looks at an object near his face, first with one eye and then with the other, he will see it in somewhat different directions. If he looks at it with both eyes it will be necessary for him to turn them in slightly. As a matter of fact, one of the best ways he has of judging distance is by the amount he has to turn the eyes in to see the object. If he looks at a distant object his eyes are sensibly parallel. In Fig. 17, the points *A* and *B* correspond to the positions of the two eyes of the observer, and the star to the object observed.

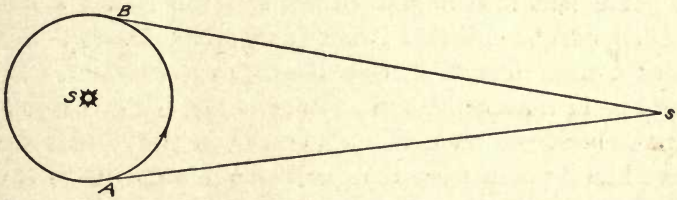


Fig. 17. The Difference in Direction of the Star *S* as Seen from the Earth at Two Different Times of the Year Proves the Revolution of the Earth

The fact that the stars should have parallaxes if the earth revolved around the sun was known at a very early date. Tycho Brahe observed them in order to discover whether they were sensibly fixed in the sky or not. So far as his observations went they did not change their positions during the year. He inferred from this that the earth remained fixed and that the sun moved. His error was due to the fact that his observations were not sufficiently accurate to show the slight displacement which the stars have. His observations were made shortly before the invention of the telescope and he could not measure the minute angles through which the stars were displaced. In fact, their distances are so great and the parallactic displacements are so small that the nineteenth century was well advanced before astronomers succeeded in finding any stars with measurable parallaxes. At the present time, in spite of the great precision of modern instruments, the parallaxes of only 50 or 60 stars have been directly measured, but these 50 or 60 prove in the most rigorous fashion that the earth actually revolves around the sun.

Revolution of the Earth Proved by Aberration of Light. The earliest direct proof that the earth revolves around the sun was made in 1728 by the discovery of what is called the *aberration of light.*

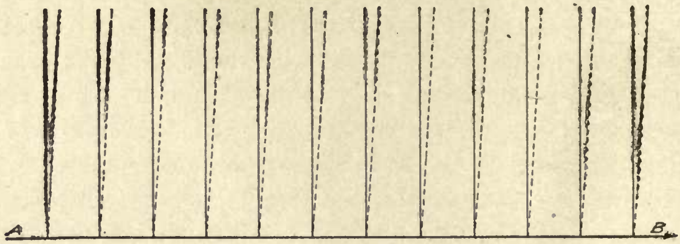


Fig. 18. The Apparent Direction of the Stars Is Slightly Changed by the Motion of the Earth across the Path of the Rays of Light from Them

Suppose rain is falling vertically and one stands still in it. Then it appears to him that it is coming straight down. Suppose he walks rapidly through it; then it seems to meet him obliquely, striking him in the face. Suppose he rides through it rapidly; then it seems to meet him more obliquely. The angle at which it seems to strike him depends upon the speed with which it falls, and the speed with which he goes across the line of its motion.

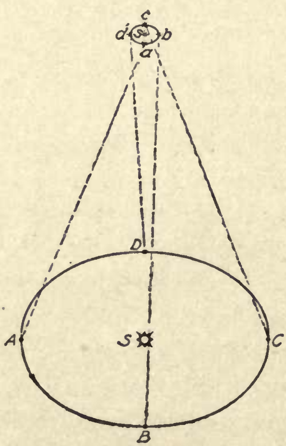


Fig. 19. A Star Apparently Describes Yearly a Small Curve in the Sky Because of the Aberration of Its Light

If one moves at right angles to the direction of the light rays a similar phenomenon is observed. In Fig. 18, suppose *AB* is the direction of the earth's motion. Suppose the continuous lines which meet it at right angles are the direction of the rays of light from a distant star. Because of the earth's motion along *AB* the rays of light from the star will appear to come in along the dotted lines. This causes the star to be apparently displaced in the direction in which the observer is going. It follows from the velocity of light and the velocity that the earth must have if it goes around the sun, that this displacement should be about 20 seconds of arc. This is a quantity which is easily observable and does not depend upon the distance of the stars. The problem is to determine by observations whether the star is thus displaced or not.

In Fig. 19, let *ABCD* represent the orbit of the earth and *s* the actual position of a star. Suppose the earth's motion is in the direction *ABCD*. When the earth is at *A* the star will be displaced by the aberration in the direction in which the earth moves and will be seen at *a*. Similarly, when the earth is at *B*, *C*, and *D*, the star will be seen at *b*, *c*, and *d*, respectively. That is, while the earth describes its orbit the star will describe an apparent small curve in the sky whose radius is about 20 seconds. This is the fact which was discovered in 1728 by the English astronomer James Bradley. The direction and the amount of the displacement agree precisely with the theory that the earth revolves around the sun, and constitute an absolute proof of its motion.

Revolution of the Earth Proved by the Spectroscope. The spectroscope is an instrument by means of which it is possible to determine whether the observer is approaching or receding from any luminous object. It enables him not only to determine whether he is approaching or receding, but also the relative speed. This is all that we need to know of the spectroscope at the present time. The discussion of the construction of this instrument and its uses will be treated in connection with the sun.

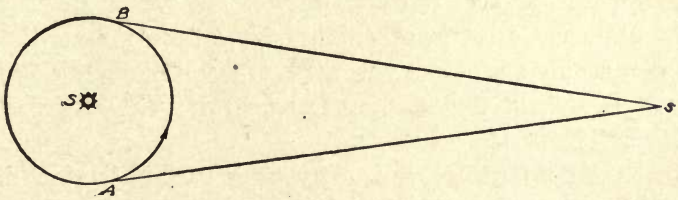


Fig. 20. When the Earth Is at *A*, It Is Approaching the Star *S*. When the Earth Is at *B*, It Is Receding from *S*. The Spectroscope Shows This Motion and Proves the Revolution

If the earth is the center of the system and the stars are fixed, the spectroscope will show that we neither approach nor recede from them. On the other hand, if the sun is the center and the earth revolves around it, the spectroscope will show that at certain times of the year we are approaching the stars and that at other times we are receding from the same stars. In Fig. 20, let *S* represent the sun and *AB* the earth's orbit. Suppose the direction of the earth's motion is indicated by the arrow. Let *s* represent the position of a distant fixed star. When the earth is at *A* it will be approaching the star and six months later when it is at *B* it will be receding from it at the same rate.

In order to determine by this method whether the sun or the earth is the center it is necessary to make spectroscopic observations of stars at the proper times. It is clear from the figure that it is most convenient to take stars in or near the plane of the earth's orbit. Now, the actual observations made on thousands of stars show us that when, according to the theory that the earth revolves around the sun, we should be approaching the stars we are actually approaching them, and that we recede when the theory demands that we should be receding. In this way the spectroscope proves with certainty that the earth revolves around the sun. It not only gives us this fact but it determines for us the speed with which it goes. Since the length of the year is known and the speed is determined by means of the spectroscope, we can compute the whole circumference of the earth's orbit, and consequently the distance from the earth to the sun. This is only one of many methods of determining this distance, and it is significant that the result agrees very closely with that found by all the other methods.

Shape of the Earth's Orbit. It was assumed in the first discussion of the subject that the orbit of the earth is circular. Obviously, this is the simplest closed curve. If the orbit is a circle with the sun at its center, then the sun will be at the same distance from the earth throughout the year and consequently will be always of the same apparent size. It is clear that an object looks smaller the farther one is away from it, but if the orbit of the earth is not a circle then its distance from the center will vary during the year and the apparent size of the sun will change correspondingly.

It is found from the actual observations of the apparent diameter of the sun that it changes throughout the year. At one time it is nearly two per cent greater than it is six months from that time.

The shape of the earth's orbit and the way in which the earth moves in it can be determined rather easily from the observations. Suppose, in Fig. 21, S represents the sun and the curve $E_1E_2E_3E_4$ the orbit of the earth (the elongation is greatly exaggerated). Suppose an observation is made when the sun is in the direction E_1S.

A convenient scale can be chosen and the line E_1S laid down. Suppose at a later date the sun is seen in the direction E_2S. The line can be laid down and the distance E_2S determined by the apparent size of the sun. If the apparent diameter of the sun is smaller when observed at E_2 than at E_1, then E_2 is farther from S than is E_1. If the diameter is one per cent smaller, then the distance is one per cent greater, and similarly for any other differences. In this fashion the point E_2 is located. In a similar way the positions of the lines E_3S and E_4S and the distances are determined, and the points which represent the position of the earth are laid down. The curve drawn through them will represent the orbit of the earth in shape, the position of the sun in its interior, and the way in which the earth moves in its orbit. Such observations as these have shown that the orbit of the earth is an ellipse, and that the sun is at one of its foci. See Fig. 5.

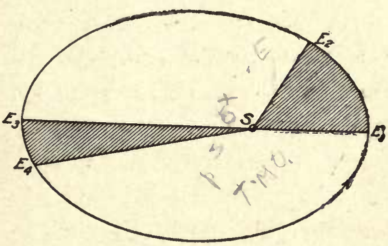


Fig. 21. The Line Joining the Earth and the Sun Sweeps Over Equal Areas in Equal Intervals of Time

It is also found that the earth moves in its orbit so that the line from the sun to it sweeps over equal areas in equal intervals of time. For example, if the time required for the earth to move from E_1 to E_2 is the same as that required for it to move from E_3 to E_4, then the area E_1SE_2 is equal to the area E_3SE_4.

Obliquity of the Ecliptic. The sun, moon, and stars as seen from the earth appear to be on a great sphere enclosing them all, which is called the *celestial sphere*. Since they are at very different distances from us they are not actually on any sphere, but only seem to be on one. In describing their directions from us it is permissible to regard them as being on this celestial sphere. The *apparent path* of the sun in its apparent yearly motion around the earth is a great circle on the celestial sphere which is called the *ecliptic*. It is not the path of the sun but the projection of its apparent path on the celestial sphere; or, it may be defined as the circle in which the plane of the earth's orbit cuts the celestial sphere.

The plane of the earth's equator cuts the celestial sphere in another great circle known as the *celestial equator*. The angle between the celestial equator and the ecliptic is called the obliquity of the ecliptic.

In Fig. 22, the line from the sun to P is parallel to the earth's axis. The circle $CABV$ represents the celestial equator, which is parallel to the earth's equator, and the circle $SAWV$ represents the ecliptic, which is in the plane of the earth's orbit. As seen from the earth the sun moves along the ecliptic from west to east, indicated in the figure by the arrow. The place where the sun crosses the equator from south to north, indicated by V in the figure, is called the *vernal equinox*, and the place where it crosses from north to south, indicated by A in the figure, the *autumnal equinox*. The earth is at a when the sun seems to be at the point A. And similarly the earth is at w, v, s when the sun appears to be at W, V, S. The axis of the earth is perpendicular to the plane of the equator and keeps always parallel to its initial direction while the earth moves around the sun.

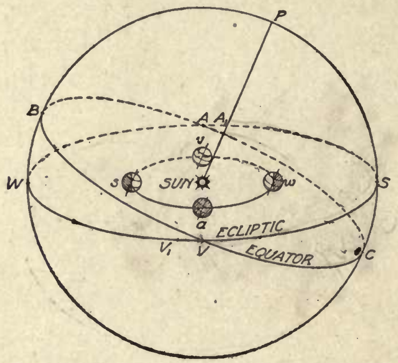


Fig. 22. The Relations of the Earth and the Plane of Its Orbit to the Ecliptic and the Celestial Equator

Precession of the Equinoxes. The ecliptic is a curve which is almost absolutely fixed in the sky. The only changes in it are due to the slight irregularities in the motion of the earth produced by the attractions of the other planets. On the other hand, the celestial equator is not fixed because the plane of the earth's equator is changed rather rapidly by the attraction of the sun and moon on the equatorial bulge of the earth. The angle between the plane of the earth's equator and the plane of the ecliptic, or the obliquity of the ecliptic, remains fixed; but the position of the plane shifts so that the points A and V go westward on the ecliptic to A_1 and V_1. Since A moves in the direction opposite to that of the apparent motion of the sun the change is called "precession." The rate is about 50.2 seconds of arc annually, from which it follows that the equinoxes will make a complete revolution only after 25,800 years have elapsed. In spite of the fact that the precession is very slow, it was discovered by the ancient Greeks three centuries before the beginning of the

Christian Era. This is an evidence of the perfection which astronomical science had attained among them.

As we shall see, the seasons depend upon the obliquity of the ecliptic. If we should define as the year for ordinary purposes the time it takes the sun to go from any apparent point on the ecliptic back to the same point again, we should find as the consequence of the precession of the equinoxes that the sun is not at the vernal equinox at the same time on succeeding years. For example, if some time it is found that the sun is at the vernal equinox precisely at the beginning of the year it will pass the vernal equinox again

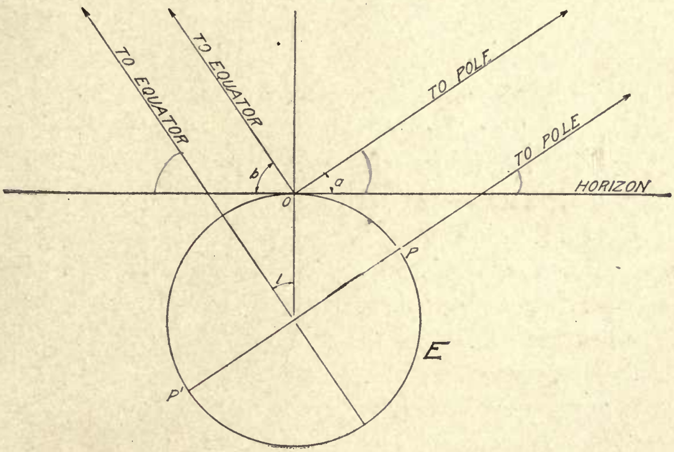


Fig. 23. The Altitude of the Pole of the Sky Equals the Latitude of the Observer

slightly before the end of the year. Consequently, with this sort of year we should have continually shifting seasons. Therefore, the year which is adopted for ordinary civil purposes is the time it takes the sun to go from the vernal equinox V around to the vernal equinox V_1, Fig. 22, which is little less than a complete revolution. Using this year, the seasons always remain fixed with respect to it.

Causes of the Seasons. The direct cause of the seasons is the varying amount of light and heat received from the sun per day. It is a matter of common observation that in the summer time the sun shines more hours per day than in the winter time and that at midday its rays fall more nearly perpendicularly. The problem before us is to discover the laws of these changes on the basis of the motions of the earth, and to apply them to a determination of the extent of the changes. As a preliminary to this discussion it will be necessary to determine the relation between the latitude of the observer and the altitude of the pole in the sky, as he sees it, and that of the equator where it crosses his meridian. In Fig. 23, let the circle E represent the earth and PP' its axis of rotation. Suppose the observer is at O; then his latitude is l. The position of the pole in the sky is that point on the celestial sphere towards which the line $P'P$ points. The celestial sphere is so remote that a line from O towards the pole will be parallel to $P'P$. The equator will be at right angles to $P'P$. The horizon of the observer at O is indicated in the figure. The angle between the plane of the horizon and the line from the observer to the pole is at a, and from the observer to the equator is b. The sides of the angle a are, respectively, perpendicular to the sides of the angle l, and it follows therefore from plane geometry that $a = l$. That is, the distance of the north pole of the sky above the north point of the horizon in degrees is always equal to the latitude of the observer. It can be seen from the figure that the angle $b = (90° - l)$. That is, the latitude of the equator on the meridian above the south point of the horizon in degrees is equal to 90 degrees minus the latitude of the observer.

As an example of these results it may be noticed that if an observer is on the earth's equator where his latitude is zero, the north pole of the sky is at the north point of the horizon; and the point where the equator cuts the meridian is directly over his head. On the other hand, if he were at the earth's pole so that his latitude were 90°, the celestial pole would be directly over his head while the equator would be on the horizon.

In Fig. 24, O represents the position of the observer and N, E, S, and W the north, east, south, and west points of his horizon. The latitude of the observer is such that the north pole of the sky is at P and the equator at $A\,W\,H\,E$. Now, because of the rotation of the earth, the sun has an apparent diurnal motion from east to west, completing a circuit of the sky in one day. Suppose the sun is at the vernal equinox, the point V in Fig. 22. Then it is on the celestial equator and it is clear that the diurnal motion is along the circle $E\,A\,W\,H$ in the direction indicated by the arrow. This is a great circle and is bisected by the horizon. Consequently, when the sun is on the celestial equator it is half of the twenty-four hours above the horizon, and the remaining half below it.

Besides this diurnal motion the sun has a slow motion along the ecliptic. After it passes the point *V* in Fig. 22, it is north of the equator, and it reaches its greatest distance north at *S*, when it is 23.5 degrees north of the equator. Now consider Fig. 24, which shows the circles of the diurnal motion. When the sun is 23.5 degrees north of the equator it moves on the circle *BKIF*. It is above the horizon while it moves over the arc *FBK*, and below it while it moves over the arc *KIF*. It is clear from the figure that it is above the horizon considerably more than one-half of the 24 hours. Six months from this time the sun will have moved around to the point *W* of Fig. 22, when it will be 23.5 degrees south of the equator. At this time its diurnal motion is along the circle *DCLG*. It is above the horizon while it describes the arc *DCL*, and below it while it describes *LGD*. It is clear from the figure that in this case the sun is above the horizon much less than one-half of the 24 hours.

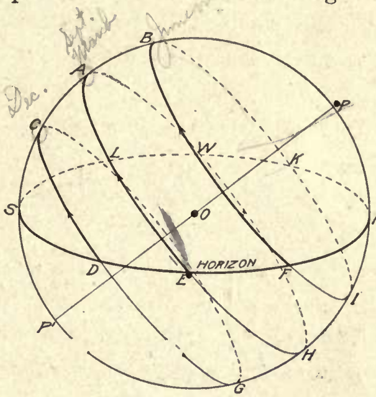


Fig. 24. The Diurnal Circles of the Sun at Different Distances from the Celestial Equator

To summarize the matter, we may state that the sun is above the horizon one-half of the 24 hours when it is on the celestial equator, whatever the latitude of the observer may be. It is on the celestial equator twice a year at the vernal and autumnal equinoxes. When it is north of the equator, moving from the vernal to the autumnal equinox, it is above the horizon more than one-half of each 24 hours. (These statements should, of course, be reversed if they are to be made for observers in the southern hemisphere.) In the six months while it is south of the equator, viz, while it is moving from the autumnal equinox to the vernal equinox, it is above the horizon less than one-half of each 24 hours. This variation in the length of sunlight per day is one of two chief causes in the changes in the seasons.

The second important reason why the seasons change is that the direction of the sun's rays at noon, for instance, varies throughout the year. In Fig. 24 the horizon *SENW* is given and it is seen that the sun's rays strike the surface of the earth at the angle *AOS* when the sun is on the equator. When it is north of the equator they strike nearer to the perpendicular at the angle *BOS;* and when it is south of the equator they strike more obliquely at the angle *COS*.

It is easy to show that the nearer the perpendicular the sun's rays strike the more they heat the surface. In Fig. 25, *AB* represents the cross-section of a certain beam of light. If the rays should strike the surface perpendicularly they would all fall on an area whose distance across would be *AB*. But if they should strike the surface obliquely, as is indicated in the figure, then the same rays would be spread over the larger area *aB*. Consequently, being spread over a larger area, they would illuminate and heat it less than when spread over the smaller area. Therefore, when the sun is high in the sky at noon it heats the surface more than it does when its rays fall obliquely. This matter is illustrated by the fact that the temperature is higher at noon, when the sun's rays fall almost perpendicularly, than it is when the sun is rising or setting.

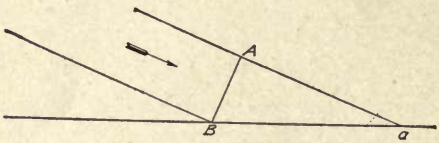


Fig. 25. When the Sun's Rays Strike the Earth Obliquely They Are Spread Out over a Large Area and Their Heating Effect Is Small

Relative Amounts of Sunlight in Different Latitudes. It is often supposed that the equatorial part of the earth is that which is not only hottest, but which receives the most hours of sunlight. It is clear from the discussion above that the northern hemisphere receives more light than the average in the summer and less in the winter, and it is at least conceivable that these two extremes exactly balance. A mathematical discussion shows that they do exactly balance for all latitudes.

In order to illustrate the matter let us take the two extreme cases, viz, where the observer is at the earth's equator and where he is at its pole. Fig. 26 represents the positions of the diurnal circles relative to the horizon when the observer is at the earth's equator. When the sun is on the celestial equator it rises at *E* and travels along the diurnal circle *EAWH*, during which time it is above the horizon. It is seen from the figure that this is exactly one-half of its whole diurnal circle. Similarly, whether it is north of the equator and moving along the diurnal circle *FBKI*, or south of the equator and moving along the diurnal circle *DCLG*, it is also exactly one-half of each 24 hours above the horizon. Therefore, at the earth's equator the sun shines exactly one-half of the time.

But when the observer is at the earth's pole, the celestial pole is directly over his head, Fig. 27, and the equator coincides with his horizon. Consequently, the sun shines only when it is north of the equator, which is one-half of the year. Therefore, in this case also the sun shines one-half of the whole year.

While the total number of hours of sunlight per year are the same at the equator and at the pole, as has just been shown, and

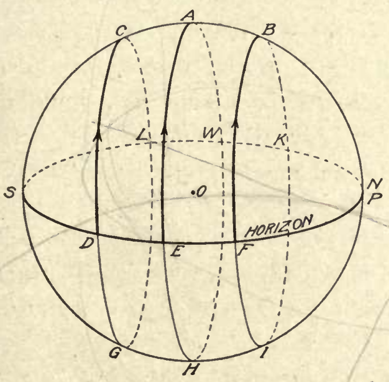


Fig. 26. Diurnal Circles for an Observer at the Earth's Equator

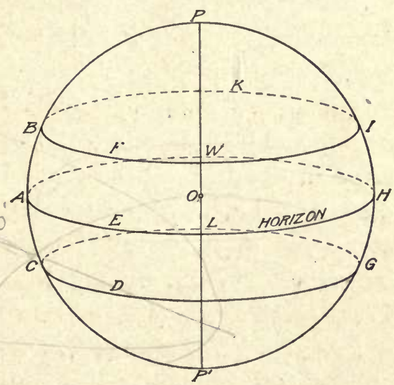


Fig. 27. Diurnal Circles for an Observer at the Earth's Pole

also in all other latitudes as can be shown by proper mathematical discussion, it is to be remarked that their distribution is very different. At the earth's equator the sun shines an equal number of hours during each day throughout the year. At the pole the sunshine is continuous for six months. It follows from this that the variation in the seasons is much greater at the pole than it is at the equator. If one were to take into account the refraction of light, which elevates the sun a distance about equal to its diameter when it is on the horizon, it would be found that the total number of hours during which the sun is visible from the pole is greater than that during which it is visible from the equator.

While the number of hours of sunshine in a year is the same for all points on the earth it must not be supposed that the total amount of sunlight received is the same for all points. On the earth's equator twice each year the sun passes through the zenith and every day passes near to it. There is, therefore, a time each day when its rays strike nearly perpendicularly on the surface. On the other hand, at the pole the sun never gets more than 23.5 degrees above the horizon and its rays always strike very obliquely. Consequently, the amount of light and heat received at the equator are very much greater than at the pole. The amount received at the equator in a year is about the same as it would be if the sun stood still 17 degrees above the horizon, for the whole year. The amount received at the pole for the whole year is about the same as it would be if the sun stood still at an angle of 5.8 degrees above the horizon. It follows from this that at the equator the amount of light and heat received are a little more than three times that received at the pole.

If it were not for the obliquity of the ecliptic, the pole would receive infinitely little sunlight because—except for the refraction—the sun would always be exactly on the horizon. Thus, it follows that the obliquity of the ecliptic causes a higher mean temperature at the pole than it would otherwise have. At the equator, on the other hand, the sun passes through the zenith but twice in the year. Consequently, the equator receives less sunlight and heat than it would if the obliquity of the ecliptic were zero. Hence, a consequence of the obliquity of the ecliptic is that the equatorial regions are cooler and the polar regions warmer than they would otherwise be; that is, the obliquity of the ecliptic has a tendency to equalize the earth's climate, taken as a whole.

An interesting fact in this connection is that, theoretically, the highest temperatures would not be found exactly at the equator. When the sun is on the equator it passes through the observer's zenith. This happens, however, on but one day, for it rapidly passes away from the equator. This is made clear in Fig. 22, since the sun is on the earth's equator when it is at *V*, which it quickly crosses. On the other hand, when the sun is near *S*, Fig. 22, its distance north of the equator changes very slowly. For some weeks it does not vary enough to make any material difference. For an observer who is just far enough north of the equator so that it then passes through his zenith, it will be above his horizon more than one-half of each 24 hours, and will pass very near his zenith each day. At this time he is receiving more light and heat than is ever received in a similar length of time by an observer at the earth's equator. It follows from this that theoretically the temperature should be highest near the points which are approximately 23.5 degrees north and south of the earth's equator.

Lag of the Seasons. From the astronomical point of view the times when the sun is at *V* and *A*, Fig. 22, are corresponding seasons. It is found from the observations that the sun is at the vernal equinox on March 21 and at the autumnal equinox on September 23. (The dates on which it passes the equinoxes can vary a day or so from those just given because of the shifting leap year.) It is perfectly clear from the point of view of the climate that March 21 and September 23 are not corresponding times in the year. The reason is the seasons lag, as we say. There is a corresponding lag in the day which, being simpler, will be first discussed.

From the standpoint of the amount of light and heat received, nine o'clock in the morning and three o'clock in the afternoon are corresponding times of day. But almost invariably the temperature is higher at three o'clock than it is at nine o'clock. The reason is that at nine o'clock the earth is receiving more heat than it radiates. This continues until noon when the maximum amount is received. But at this time it is also receiving more than it radiates and continues to do so until the increase of its temperature and the decrease in the amount received cause the radiation to equal exactly that which is received. After that the temperature begins to fall. But under normal weather conditions this occurs considerably after noon. The time after noon at which the highest temperature is reached is called the lag of the noon. There is a corresponding lag in the time of lowest temperature at night. Of course, when the sun has set no light and heat are received from it directly until morning, but it is farthest below the horizon at midnight. Instead of this being the time of the lowest temperature, as a rule the temperature steadily falls from sundown until almost sunrise in the morning.

Now consider the seasons. As the sun mounts higher and higher in the sky in the spring so that more and more heat is received daily, the earth gets considerably warmer both because of the greater number of hours of sunshine and also because of the high altitude of the sun at noon. During the spring months, for example, April and May, the earth receives more heat in the northern hemisphere than is lost by radiation, and the temperature rises. This continues until about the 21st of June when the sun arrives at the point *S*, Fig. 22, which is its greatest distance north of the equator. But at this time the maximum amount of heat is received and this is more than that which is radiated. Consequently, the mean temperature continues to rise for some time after the 21st of June. It becomes stationary only when the temperature rises to such a point that the increased radiation and the decreased amount received exactly balance. In moderate latitudes this lag amounts to some weeks.

If the earth had no atmosphere and if it radiated the heat as fast as it was received there would be no lag of the seasons. Atmosphere is one of the causes of the lag of the seasons. The more it absorbs light and heat as they come to the earth, and prevents their escaping as the earth radiates them out, the more the seasons will lag. It is a matter of common observation that there is a greater lag to the seasons in low altitudes, especially where the atmosphere is moist, than there is on the high and dry plateaus.

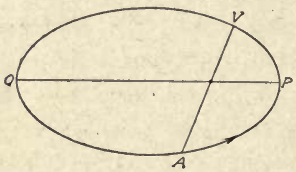


Fig. 28. The Summer and Winter Seasons Are of Unequal Length Because of the Eccentricity of the Earth's Orbit

Effect of the Eccentricity of the Earth's Orbit upon the Seasons. In the discussion up to this point it has been assumed tacitly that the orbit of the earth around the sun is a circle. As explained above, it is an ellipse and the earth is about three per cent nearer at the point nearest the sun than it is when most remote. Consequently, the amount of light and heat received depends to some extent upon the varying distance of the earth from the sun. It should be said, however, that this is not so important a cause as that discussed above.

There is a very interesting indirect result of the eccentricity of the earth's orbit, viz, that the seasons in the northern and southern hemispheres are not of equal length. In Fig. 28, *V* represents the position of the earth when the sun is at the vernal equinox, and *A* its position when the sun is at the autumnal equinox. The point *P* is the earth's position when it is nearest the sun. It is almost midway between A and V, but a little nearer V than A. It follows from the law of areas that the earth will pass from A through P to V in a shorter time than is required for it to pass from V through Q to A. If we count the days from March 21 to September 23 it is found that the summer, from the astronomical point of view, in the northern hemisphere is 186 days and the winter, viz, the time from September 23 to March 21, is 179 days. The more exact figures are: the length of the summer in the northern hemisphere is 186¼ days, and the winter 179 days. That is, because of the eccentricity of the earth's orbit, the summer is 7¼ days longer than the winter. In the southern hemisphere the conditions are reversed.

One might suppose from this that there were peculiar climatic advantages in the northern hemisphere. The facts are, however, that the same amount of light and heat are received in the year at any point in the northern hemisphere as are received at any point having an equal latitude in the southern hemisphere. The increase in the length of the summer in the northern hemisphere is exactly offset by the greater distance from the sun during this time, and its nearness to the sun in the winter in the northern hemisphere is exactly compensated by the fact that the winter is shorter. The more exact statement is that equal latitudes in the northern and southern hemispheres receive exactly the same amount of light and heat in corresponding parts of any seasons. The chief difference is that in the northern hemisphere the tendency is for the climate to be somewhat more uniform, since, when the rays strike nearest to the perpendicular, the earth is farthest from the sun. The conditions are reversed in the southern hemisphere. The fact, however, that there is so much more water in the southern hemisphere than there is in the northern, probably more than counterbalances these astronomical causes for an equable climate in the northern hemisphere.

The eccentricity of the earth's orbit slowly changes and the direction of its major axis PQ also chan es because of the attractions of the other planets for it. Likewise it was seen above that there is a precession of the equinoxes, so that the line AV does not remain fixed. It follows from this that not only does the elongation of the orbit of the earth change, but also the positions of the lines PQ and AV change relative to each other. In about 10,000 years from now the conditions will be the opposite of those we have at present. At that time the summers in the northern hemisphere will be shorter than the winters and more heat will be received per day than during the summers in the southern hemisphere. In the course of a very long time, counted by tens of thousands of years, the eccentricity of the earth's orbit will be greater than it is at present, though now it is decreasing and will decrease very slowly for a long time.

It has been supposed that an unequal distribution of the light and heat received from the sun throughout the year are favorable to glaciation. An English geologist, Croll, suggested, as an explanation of the ice ages which the earth has experienced, that they were due to the fact that at certain times the northern hemisphere had long, cold winters and short, hot summers. He supposed that the accumulation of ice and snow in the winter time, under those circumstances, would be so great that they would not be melted in the summer. This theory has been abandoned because, according to it, the intervals between the ice ages would be counted by hundreds of thousands of years, whereas geologists find they were much closer together than this. Likewise there have been ice ages very probably at the same time in both the northern and southern hemispheres. According to this theory, when the conditions are favorable to glaciation in one hemisphere they are unfavorable to it in another, and glaciation should not be simultaneous both north and south of the equator.

STAR CLUSTER AND NEBULA IN CYGNUS

Taken with a 10-inch Bruce lens. The streak at the top of the picture was made by a large meteor

ASTRONOMY

PART II

THE CONSTELLATIONS

Problem of Locating the Constellations. The most careless observer of the sky has noticed that the stars are not uniformly spread over it. Almost everyone is familiar with the Big Dipper and the Pleiades, otherwise known as the Little Dipper. These natural groups of stars were given names in antiquity by early observers and are called *constellations*. Their names often strike us as being most fantastic and far-fetched. Many of them are the names of wild animals. For example, we have the Great Bear, the Lesser Bear, the Lion, the Eagle, the Leopard, etc.

If the sky is watched for a few hours it is observed that these groups of stars move across it from the east toward the west. The fact that they are not fixed in the sky leads to some little difficulty in describing their positions. Suppose an observer watches them a few nights until he finds how they move throughout the night and knows where they appear at any time of the night. If he then ceases to observe them for a few months and again returns to his observations, he will find things are quite different. Those stars which at his first observations were visible high in the sky late in the night are a few months later visible early in the evening. Thus, he finds that not only do the stars change their positions in the sky during the night but that on successive nights these positions are not the same. There is a continual shift throughout the year.

It follows from these changing positions of the stars and the necessity in certain astronomical work of locating them with the very highest degree of precision, that it is necessary to adopt some machinery for describing their positions. As was stated above, all the heavenly bodies seem to be seen on a great sphere. This sphere, surrounding the visible universe and having the earth as its center, is called in astronomy the *celestial sphere.* The problem of the astronomer is to locate the positions of the heavenly bodies on this sphere, which is in many respects similar to the problem of locating the position of a place on the earth, which for ordinary geographic purposes may be regarded as a sphere. From the standpoint of geometry the two problems are exactly the same. They appear to us to be slightly different because in the case of the earth we are on the outside and in case of the celestial sphere we are on the inside. But in representing the celestial sphere by a globe we are on the outside, and this is sometimes a little confusing. However, by a little use of the imagination the identity of the two problems can be seen, and our knowledge of what is done in geography will assist in understanding how the corresponding problem is solved in astronomy.

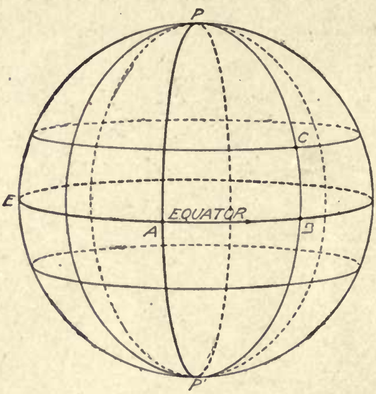


Fig. 29. The Latitude and Longitude Circles on the Earth

Geographical System. The lines on the earth by means of which we locate places fall into two fundamentally distinct systems: (1) there are the equator and the system of small circles parallel to it; (2) there are the great circles which pass through the poles of the earth and cut the equator at right angles. The circles to be defined are the equator (after which all the parallel circles are given) and the particular great circle perpendicular to the equator from which we count.

In locating the position of a place on the earth, we give its distance north or south of the equator, called its *latitude,* and its distance east or west of some selected meridian, called its *longitude.* The meridian is selected for its convenience, the ones in most common use being those through the Royal Observatory at Greenwich, England, the one through the Naval Observatory at Washington, and those in other countries passing through their national observatories. The position of Chicago, for example, is about 41° 50′ north of the equator and 78° 22′ west of the meridian of Greenwich.

In Fig. 29, *EAB* represents the equator and *PP′* the poles. Suppose the meridian *PAP′* is the fundamental meridian from which longitudes are counted. Consider a point at *C*. The latitude is the arc *BC*, and the longitude is the arc *AB* measured along the equator. It is to be noted that it must be measured along the equator because the latitude circle through *C* is a small circle.

Horizon System. In defining the circles of this system it is simpler to start with the zenith than with the horizon. The *zenith* is the point overhead where the plumb-line extended upward pierces the celestial sphere. The *nadir* is the point below 180° from the zenith. The *horizon* is the great circle of the celestial sphere 90° from the zenith and nadir. This is the astronomical horizon and it may differ in particular instances considerably from the sensible horizon which is determined by the apparent union of earth and sky, and depends, obviously, upon all sorts of irregularities. The horizon corresponds to the equator in the Geographical System. The small circles parallel to the horizon, corresponding to the circles of latitude in the Geographical System, are called *parallels of altitude.*

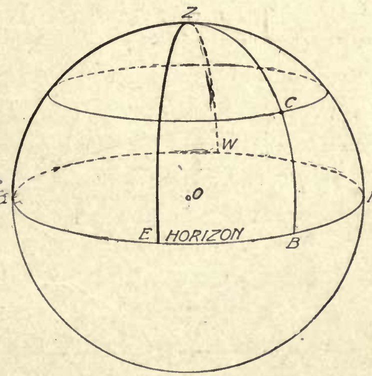


Fig. 30. The Horizon System of Circles

The circles corresponding to the meridians in the Geographical System are the circles on the celestial sphere which pass through the zenith and nadir and cut the horizon perpendicularly. They are called *vertical circles* because they cut the horizon vertically.

The position of a point on the celestial sphere is determined by giving its distance above or below the horizon and its distance corresponding to longitude. The distance from the horizon is called the *altitude,* plus if above and minus if below.

The vertical circle from which the other distances are counted is the one passing through the zenith and the south point. This second distance, which is called *azimuth,* is counted westward from the south point around to the foot of the vertical circle through the object in question. Thus, in Fig. 30, suppose *C* is a celestial object whose altitude and azimuth we wish to give. Its distance above the horizon measured along the vertical circle is *BC*, which is its altitude. Its azimuth is the arc starting from *S* measured westward through *W* and *N* to *B*, which, in the present example, is somewhat greater than 180°. In this respect the scheme differs a little from the Geographical System, where longitudes are counted both eastward and westward, and azimuth only westward. There is nothing fundamental in this method, but it is found simpler to count it all the way around to 360 degrees, rather than to be under the necessity of always stating whether it is counted eastward or westward.

The reason that azimuth is counted westward instead of eastward is that the stars in their diurnal motions go from east to west across the sky. Counting the azimuth westward, we find that it increases as the night goes on. When a star is on the meridian its azimuth is zero and as it passes west of the meridian its azimuth steadily increases. If the azimuth were counted in the other direction from the south point, then the azimuth of a star, as it crosses the meridian, would pass from zero to 359 degrees, and then continually decrease. The inconvenience of such a method as this is at once evident.

Equator System. In defining the Equator System it is simplest to start with the celestial pole. In this work reference will be continually made to the north pole, since we live in the northern hemisphere of the earth, but corresponding statements can in every case be made for the southern pole. The celestial pole is the center of the diurnal circles which the stars describe (see Fig. 11); or it is the place where the earth's axis extended northward pierces the celestial sphere.

In Fig. 31, let *O* be the position of the earth and *P* and *P′* the positions of the celestial poles. The celestial equator is the great circle on the celestial sphere 90 degrees from the celestial pole, or it is the great circle in which the plane of the earth's equator cuts the celestial sphere. The small circles parallel to the celestial equator are called parallels of *declination.* In Fig. 31 *VEB* represents the equator and *DCF* a parallel of declination.

The celestial equator corresponds to the earth's equator in the Geographical System, and the parallels of declination correspond precisely to the parallels of latitude. In fact, these circles on the celestial sphere are parallel to the corresponding ones on the earth.

The circles which correspond to the meridians on the earth pass through P and P', Fig. 31, and are perpendicular to the equator. They are called *hour circles* for reasons which will be explained presently. The fundamental hour circle from which distances are counted is the one which passes through the vernal equinox, represented by V in Fig. 31.

The distance north or south of the equator, corresponding to latitude on the earth, is *declination;* positive if north, negative if south. The distance corresponding to longitude on the earth is *right ascension,* which is counted *eastward* from the vernal equinox along the equator to the foot of the hour circle through the object. This differs from longitude on the earth in that it is counted only in one direction.

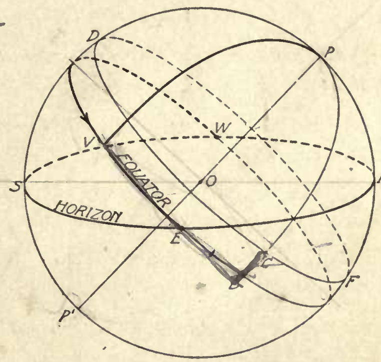


Fig. 31. The Equator System of Coordinates

If one wishes to give the position of C, Fig. 31, in the Equator System, he gives its declination, which is the arc BC, and its right ascension, which is the arc VB, measured eastward from V through E to B.

Since the earth rotates on its axis from west to east, the sky apparently rotates from east to west. The point V is not a fixed point on the apparent sky, as one looks at it. It rises in the east at E daily, goes across the sky to the west and sets at W, passing around to E again. The star at C passes along the declination circle through D around to F and back to C daily. Its highest altitude is when it is on the meridian at D. It was shown above that the altitude of the equator on the meridian is 90 degrees minus the latitude of the observer. Consequently, the highest altitude of a star is 90 degrees minus the latitude of the observer plus the declination of the star. For example, if an observer is 40 degrees north of the equator and he observes a star whose declination is twenty degrees north, he finds that when it crosses its meridian its altitude is $90° - 40° + 20° = 70°$.

Its lowest altitude is when it is at F; on the point where the equator cuts the antimeridian NP', it is 90 degrees minus the latitude of the observer below the horizon. The lowest altitude of a star in its diurnal motion is therefore 90 degrees minus the latitude of the observer, plus the declination of the star. For example, in the problem given above the lowest altitude of the star is $-90°+40°+20°=-30°$, or 30 degrees below the horizon. In this way it is found that, for an observer in latitude 40 degrees, the highest altitude of the sun, when it is at the summer solstice 23.5 degrees north of the equator, is 73.5 degrees, and its lowest altitude below the horizon is 26.5 degrees. In the winter time, when the declination of the sun is 23.5 degrees south, it is found in a similar way that its highest altitude in the day for an observer in latitude 40 degrees north is 26.5 degrees and its lowest altitude is -73.5 degrees.

The reason that the circles passing through *P* perpendicular to the equator are called hour circles is that they move from east to west across the sky in their diurnal motions, making a circuit in 24 hours. Consequently, if they are drawn one hour apart they will cross the meridian one after another at intervals of an hour. For this reason it is customary to count right ascension in hours rather than in degrees, though the relation is simple. The 360 degrees around the celestial equator are divided into 24 hours, from which it follows that one hour is equal to 15 degrees.

It is readily seen from this how easy the problem of determining the right ascension of the stars is if one has a clock and a telescope mounted in the plane of the meridian. Suppose he keeps the telescope fixed and makes a record of the time the stars pass across its field, which is the time they pass the meridian. Suppose his clock is set so that it registers zero hours when the vernal equinox passes the meridian, and that it is marked to run from zero to 24. Then if a star passes at one o'clock its right ascension is one hour, and similarly for any other time. This is, in fact, the way the right ascensions of the stars are determined. At the same time their declination can also be determined. If it is found how high they are above the horizon when they pass the meridian, their declination is at once given because their declination is equal to their altitude minus the altitude of the equator. If they are north of the equator, and consequently have an altitude greater than the equator, this comes out a positive result. On the other hand, if they are south of the equator their declination comes out negative. These results agree with the definitions of positive and negative declination given above. Since the altitude of the equator is 90 degrees minus the latitude of the observer, it follows that the declination of the star is its observed altitude plus the latitude of the observer minus 90 degrees.

Ecliptic System. The ecliptic has been defined as the apparent path of the sun around the celestial sphere. It is a great circle cutting the celestial equator at the vernal and autumnal equinoxes and inclined to it by an angle of 23.5 degrees. In Fig. 32, *KEMW* represents the celestial equator and *LVJA* the ecliptic, which cuts the equator in *V* and *A*. As before, *SWNE* represents the plane of the horizon.

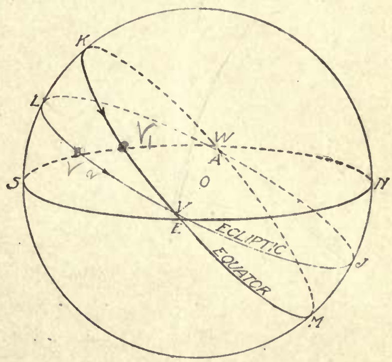


Fig. 32. The Relation of Horizon, Ecliptic, and Equator

The parallels to the ecliptic, which are not given in the diagram, are called the *parallels of latitude.* The distance north or south of the ecliptic is called the *latitude.* The great circles perpendicular to the ecliptic are called *celestial meridians.* The fundamental one from which distances along the ecliptic are counted is the one passing through the vernal equinox. It follows that the fundamental hour circle and the fundamental celestial meridian intersect at the vernal equinox. They do not, of course, coincide because the former is perpendicular to the celestial equator and the latter to the ecliptic. The distance from this fundamental celestial meridian counted *eastward* along the ecliptic to the foot of the celestial meridian through the object is called the *celestial longitude.* It is counted eastward until the object is reached even up to 360 degrees. Since the vernal equinox goes around the sky in the diurnal motions of the heavens, as has been explained above, the Ecliptic System revolves in a similar fashion, but in this case the motion with respect to the horizon is considerably more complex than in the case of the Equator System. For one-half of the 360 degrees the ecliptic is above the equator, and for the other one-half it is below it. Consequently, during one-half of 24 hours the ecliptic cuts the meridian at a greater altitude than the equator, and during the other half at a lesser altitude. The ecliptic cuts the meridian in 24 hours at all the altitudes at which the sun crosses the meridian in a whole year. The reason for this is, of course, that the sun passes around the ecliptic once in a year.

Comparison of Systems. If one person were to describe to another verbally where certain stars could be seen it would evidently be the simplest for him to give their altitude and azimuth. He would immediately look into the sky and locate the objects. But if he were to write to a person in another place serious difficulties would arise. In the first place, the one who was to observe the celestial objects would see them at a different time. In general it would be both at a different time of the day and a different time of the year. Consequently, the description would fail unless additional data were given, because, as was stated in the beginning of the discussion of the Horizon System, the altitude and the azimuth of the stars not only change during the night but for a given time of night change through the year.

There is another reason why the Horizon System would not be simple unless the observer were to look at the place where the person was who gave him the description. This second reason is that the position of an observer's horizon depends upon his location on the earth. This follows obviously from the fact that the zenith, and therefore indirectly the horizon, depends upon the direction of the plumb line of the observer. Altogether, therefore, in order to use the Horizon System as a means of describing the location of celestial objects it is necessary not only to give their altitude and azimuth but also the time of day, the day of the year, and the position of the observer. Obviously, for catalogue purposes, this system is inconvenient. In a word, this system of reference points and lines slides on a celestial sphere.

The Equator System is distinguished by the fact that its reference points and lines are fixed among the stars. The position of the celestial pole and the celestial equator are altogether independent of the observer's position. Likewise the vernal equinox, from which the right ascensions are counted, is independent of the observer's position, the time of the day, or the time of the year. A slight correction to this statement is necessary because of the precession of the equinoxes as explained above. This is a very slow process and need not be considered in the present connection.

The Equator System is fixed on the celestial sphere and is well adapted for cataloguing purposes. To locate a star by it we need only to give its right ascension and declination. That locates it permanently and for any place and time. In order for an observer to see the object he must calculate in some way where it will be as seen from his position at the time he wishes to view it. The Equator System is the one actually used in all catalogues. The right ascensions and declinations are determined essentially as described above.

The Longitude System is similar to the Equator System in that it is fixed on the celestial sphere. If a point is given in terms of the celestial latitude and longitude it is uniquely located, but this system is not in so common use as the equatorial because it does not connect so easily with the observations made by the telescope fixed in the plane of the meridian in connection with the astronomical clock. Its principal uses are in describing the positions of the sun, moon, and planets, which never depart very far from the ecliptic.

Determination of Right Ascension of Meridian at Any Time. Since the catalogues use the Equator System and the observers depend upon the Horizon System, it is necessary in order to use a catalogue in making observations to establish the connection between the two systems. Suppose the right ascension of a certain star is given and it is desired to know whether it is visible at the time in question or not. If its right ascension is the same as that of the meridian it will be on the meridian and will be visible provided it is not too near the southern pole of the sky. On the other hand, if its right ascension is 12 hours from that of the meridian it will be on the opposite side of the earth and invisible unless it is near the north pole of the sky so as to be above the horizon. The right ascension of the star being given in the catalogue, the problem of determining whether it is visible or not is reduced to that of finding the right ascension of the meridian at any time. We shall now consider this problem.

The sun is found by observation to be at the vernal equinox on March 21 of each year. (This date may vary by a day because of the accumulated errors which are adjusted every four years by the leap year.) It moves eastward along the ecliptic at a nearly uniform rate, the variation from uniformity being expressed by the law of areas. For present purposes it is sufficiently exact to suppose it moves eastward uniformly along the equator, which is represented by the circle *MEAW* in Fig. 33. Since it makes the circuit of the heavens in 12 months, and since the circumference is divided into 24 hours of right ascension, it follows that the sun moves eastward from the vernal equinox about two hours each month. Consequently, to find the right ascension of the sun, it is necessary only to count the number of months from March 21 to the day in question and to multiply by two. Thus, on June 21, which is three months after the sun passes the vernal equinox, the right ascension of the sun is approximately six hours. On October 21, which is approximately seven months after the sun passes the vernal equinox, the right ascension of the sun is 14 hours.

We wish, however, the right ascension of the meridian at the time in question instead of the right ascension of the sun. We shall make the determination of the right ascension of the sun the first step in solving this problem. If it is the stars we wish to observe they necessarily will be seen at night and the most convenient time is in the early part of the night. Suppose, therefore, that as a practical problem we determine the right ascension of the meridian at eight o'clock on any night. By the method described above the right ascension of the sun is found, whose position is indicated by *s* in Fig. 33. Now the right ascension is counted eastward. Consequently, the right ascension of the meridian *M* is equal to that of the sun plus the angular distance *sWM*. If it is 8 o'clock P. M. the sun has passed the meridian eight hours and the arc *sWM* is eight hours. For example, on June 21 the right ascension of the sun is six hours and the right ascension of the meridian at 8 P. M. is 6+8=14 hours. If one wished to locate the vernal equinox, which would be less convenient to use, it would be found six hours west of the sun.

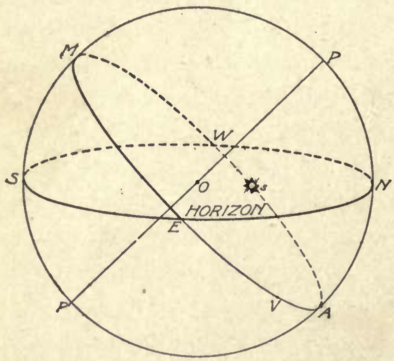


Fig. 33. Determination of the Right Ascension of the Meridian

Similarly, on October 21 the right ascension of the sun being 14 hours, the right ascension of the meridian at 8 P. M. is 22 hours.

In the two examples the stars that are on the meridian at the times in question are, respectively, those whose right ascensions are 14 hours and those whose right ascensions are 22 hours. The problem is solved in an exactly similar manner for any other day and time of day.

Application of Declination to Location of Stars. It is evident that the visibility of a group of stars depends not only upon their right ascension but also upon their declination. In Fig. 24, it was shown that when the sun is north of the equator it is visible more than one-half of the 24 hours, while if it is south of the equator it is visible less than one-half of the 24 hours. That is, when the sun is north of the equator it is visible at a greater distance from the meridian than it is when it is south of the equator. Since the diurnal motion of the sun is parallel to the diurnal motions of the stars the same thing is true of them. The difference is that the stars always have sensibly the same declinations and any statement made for them at one time holds for all time. Another difference is that the stars extend all the way from one pole to the other. Those which are on the equator, half of which is above the horizon, are visible only if they are less than six hours east or west of the meridian.

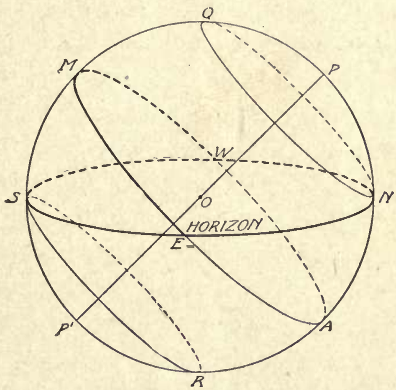


Fig. 34. The Diurnal Circles of the Stars. Those near the North Pole are always above the horizon and those near the South Pole are never visible.

For practical observations it is necessary that the stars should be some little distance above the horizon, though theoretically they are visible until they arrive at the horizon. Stars which are north of the equator are visible even though their distances from the meridian east or west are somewhat greater than six hours, the amount depending on how far they are north. In Fig. 34, it is seen that those which are near enough the pole, viz, in sector *NQP*, are always visible. The pole *P* is the center of the diurnal circles and the distance *NP* is equal to the distance *PQ*. It was shown above that *NP* is equal to the latitude of the observer. Therefore, those stars whose distance from the pole of the sky is less than the latitude of the observer are always visible to him. Around the southern pole of the sky there is a similar region of equal area, $SP'R$, in which the stars are never visible. If a star's declination is so far south that its distance from the southern pole is less than the latitude of the observer then he will never see it.

If an observer is at the earth's equator all the stars are visible to him in the course of time. Those which are at the poles of the heavens are on the north or south horizons. Those which are at the celestial equator rise in the east, pass through the zenith, and set in the west. But if an observer were at the pole of the earth the pole of the heavens would be at his zenith and the celestial equator on his horizon. Therefore, only one-half of the celestial sphere would ever be visible to him. The diurnal motions of the stars would be in circles parallel to the horizon.

Origin of Constellations. Nearly all our constellations (groups of stars) have been handed down to us from prehistoric times. They had their origin, probably, in Babylonia and Egypt and were transmitted to us through the Greeks and the Arabians. Many of the names of the stars as well as of the reference points and lines are of Arabic origin, having been translated into this tongue from the more ancient ones. Thus the words *zenith, nadir, horizon, azimuth,* etc., are Arabic. The names of most of the bright stars are also Arabic. Those observers who originally named the constellations lived in the northern hemisphere, and there were certain stars in the vicinity of the south pole of the sky which were not visible to them. Consequently, in this part of the sky the stars were given no names. There were also certain places in the northern heavens where the stars were not very conspicuous, which were not covered by the constellations of the ancients. To fill up these gaps a few constellations have been added in modern times.

The outlines of the constellations are extremely irregular and the stars situated in them generally give no suggestion whatever of the names which have been assigned to them. By the wildest stretch of the imagination it is not possible for us to see that the stars which constitute Leo have any resemblance to the outline of a lion, and equally dissimilar to their names are the other constellations.

A list of the constellations is given in Table I. In the left-hand column their right ascensions are given and at the top of the

TABLE I

List of Constellations with Right Ascensions and Declinations

Dec. / R. A.	+90° to +50°	+50° to +25°	+25° to 0°	0° to −25°	−25° to −50°	+50° to −90°
I–II	Cassiopeia 46	Andromeda 18 Triangulum 5	*Pisces* 18 *Aries* 17	Cetus 37	Phoenix 32 Apparatus Sculptoris 13	(Phoenix) Hydrus 18
III–IV	....	Perseus 46	*Taurus* 58	Eridanus 64	(Eridanus)	Horologium 11 Reticulum 9
V–VI	Camelopardalus 36	Auriga 35	Orion 58 Gemini 33	Lepus 18	Columba 15	Dorado 16 Pictor 14 Mons Mensa 12
VII–VIII	....	Lynx 28	Canis Minor 8 *Cancer* 15	Canis Major 27 Monoceros 12	Argo Navis 149	Piscis Volans 9
IX–X	....	Leo Minor 15	*Leo* 47	Hydra 49 Sextans 5		
XI–XII	Ursa Major 53	....	Coma Berinices 20	Crater 15 Corvus 8	Centaurus 6	Chameleon 13
XIII–XIV	....	Canes Venatici 15 Bo¨tes 36	....	*Virgo* 39	Lupus 34	Crux 13 Musca 15
XV–XVI	Ursa Minor 23	Corona Borealis 19 Hercules 65	Serpens 25	*Libra* 23	Norma 14	Circinus 10
XVII–XVIII	Draco 80	Lyra 18	Aquila 37 Sagitta 5	*Scorpio* 34 Ophiuchus 46	Ara 15	Triangulum Australis 11 Apus 8
XIX–XX	....	Cygnus 67	Vulpecula 23 Delphinus 10	*Sagittarius* 48	Corona Australis 18	Telescopium 16 Pavo 37 Octans 22
XXI–XXII	Cepheus 44	Lacerta 16	Equuleus 5	Capricornus 22	Piscis Australis 16	Indus 15
XXIII–XXIV	....	....	Pegasus 43	*Aquarius* 36	Grus 30	Toucana 22

columns are their declinations. In connection with each constellation a number will be observed which indicates the number of conspicuous stars in the constellation. The names of certain constellations are printed in italics. These are the stars which lie along the ecliptic and are called the *signs of the zodiac.* The ancients always spoke of the sun as being in a certain sign or constellation, as in Scorpio, Sagittarius, etc. It is easy for us to determine at what time of the year the sun is in a given constellation. For example, from the list of constellations we see that the right ascension of Scorpio is XVII – XVIII hours. The sun has a right ascension of 18 hours at $18/2=9$ months after March 21, or December 21.

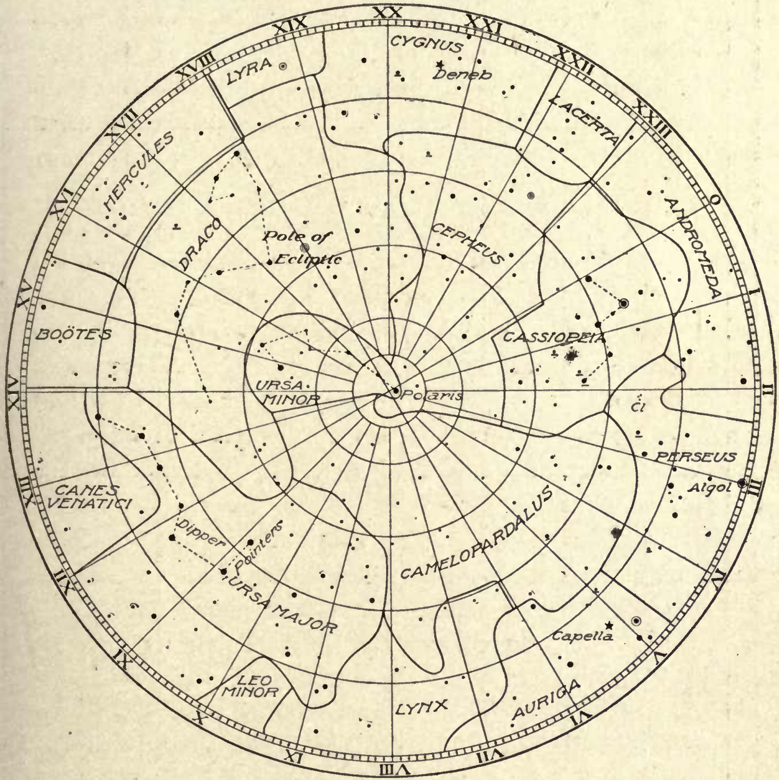
Suppose it is required to find at what time of the year Leo is visible at 8 P. M. From the table it is seen that its right ascension is ten hours. If it is to be on the meridian the right ascension of the meridian is therefore ten hours on the day in question. The sun being eight hours west, and right ascension being counted eastward, the right ascension of the sun will be $10-8=2$ hours. The right ascension of the sun is two hours on April 21. Therefore, the constellation Leo is on the meridian April 21 at 8 P. M. In this way the table can be used to find at what time of the year any constellation is on the meridian at eight o'clock at night, or at any other hour of the night. It should be used in locating the stars, especially in connection with the star maps.

Maps I, II, III, and IV give all the constellations except those within 40 degrees of the south pole of the sky, which are not visible in the latitude of the United States. Map I shows those around the north pole of the heavens. It is made so it can be used by determining *first* the right ascension of the meridian at the time in question; and *second* by turning the map so that this hour of right ascension which is marked on its margin, is above the pole; then the map is held up so that its center is seen by the eye in the direction of the pole of the sky. When the map is turned around in this way to the sky the positions of the stars located on it are the same relatively as those in the sky.

Suppose, for example, that the time the observer uses it is May 21, at 8 P.M. The right ascension of the sun on this date is four hours, and of the meridian at this time 12 hours. Consequently, the hour circle marked 12 in the map must be held directly above

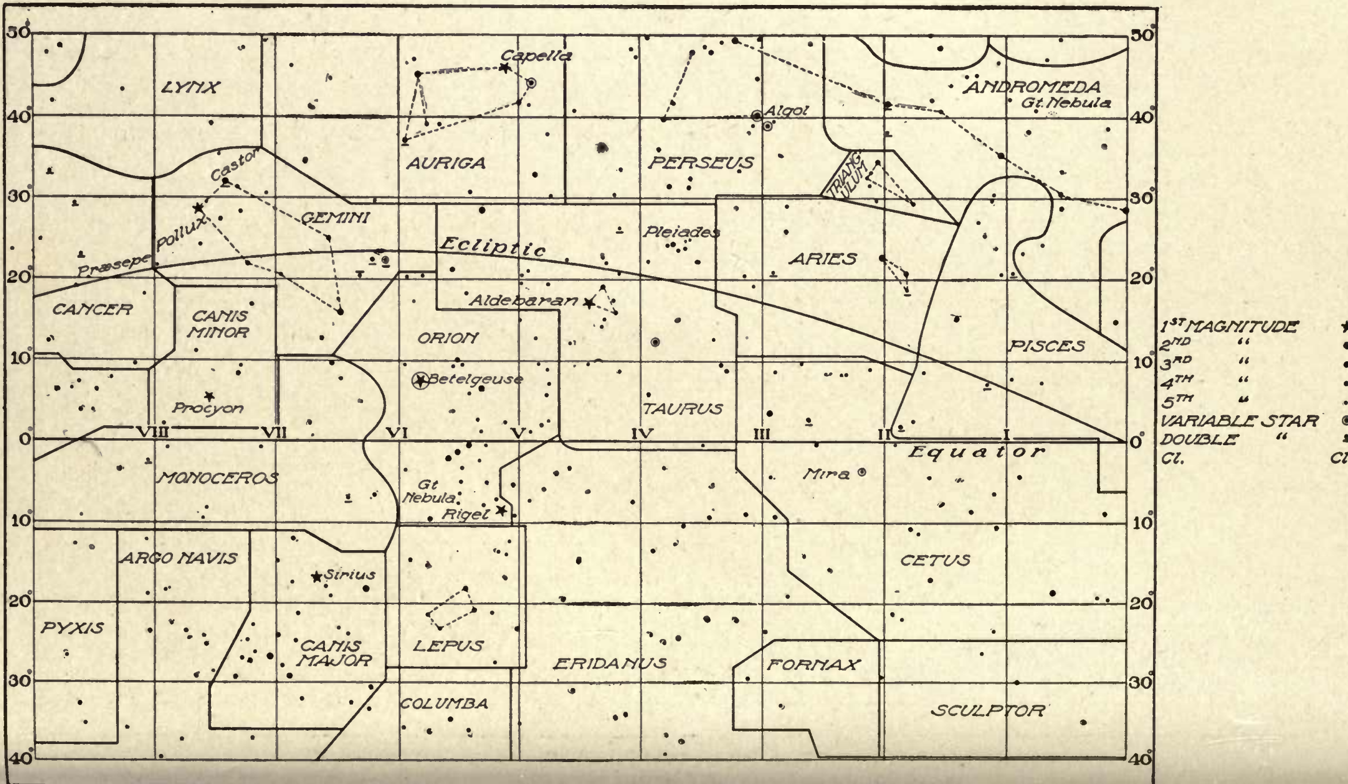
MAP I

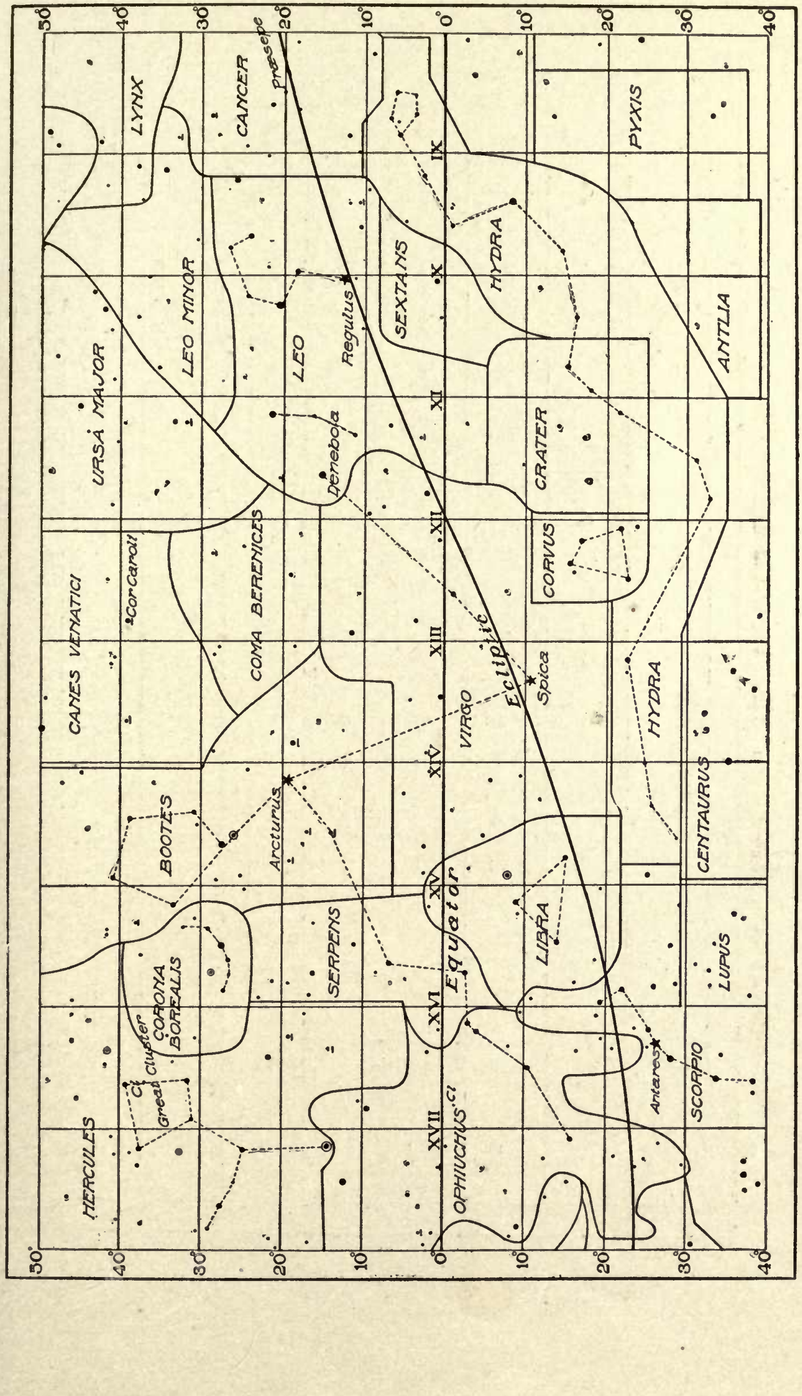
Constellations Around North Pole of the Heavens



1ST MAGNITUDE ★
2ND " ●
3RD " •
4TH " ·
5TH " :
VARIABLE STAR ●
DOUBLE " ∸
CLUSTER Cl
POLE of ECLIPTIC ●

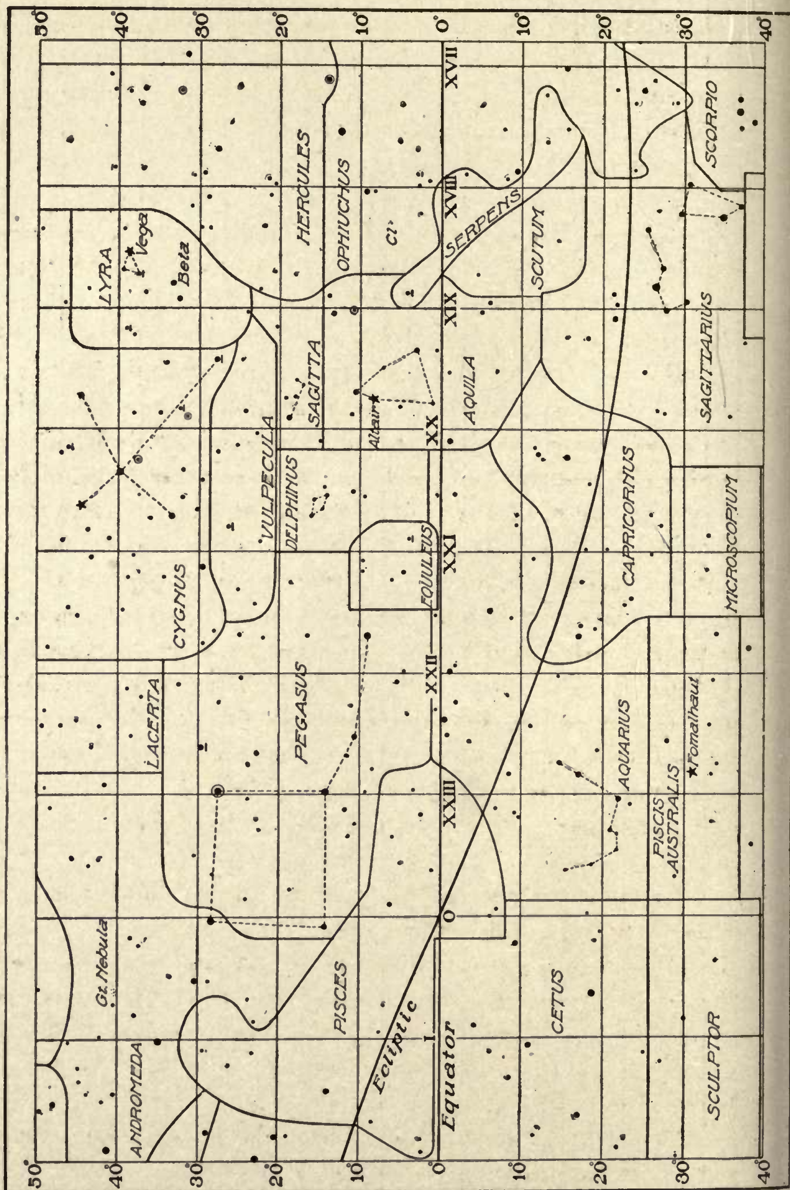
MAP II
Constellations in Region of Equator. Right Ascension 0 to IX





MAP III

Constellations in Region of Equator. Right Ascension VIII to XVIII



MAP IV

Constellations in Region of Equator. Rigbt Ascension XVII to XXIV its center. As the map is looked at on the page this is the lower left-hand part. When this is turned around, so it is up and the map held to the sky, it is seen at once that the Big Dipper is above the pole, that Cassiopeia is directly below the pole, that Camelopardalus is to the west of the pole, and that Draco is to the east of it. In a similar way it can be used for any other time of the year and of the night.

The other maps give the region along the equator. Consider the time May 21, at 8 P. M. The right ascension of the meridian, as has been stated, is then 12 hours. It is seen by referring to the right ascension marks, which are on the center line of these maps, that Map III must be used in this case. The mark XII is found on this map where the ecliptic crosses the equator from north to south. If the map is held up to the southern sky, so that this point is on the meridian at the height of the equator, then the stars will be spread out relatively on the map the same as they are on the sky. It will be seen then that Leo is a little west of the meridian and a little higher than the equator. On the meridian south of the equator and a little to the west is the constellation Crater. On the meridian and a little west of it, running across the equator, is the zodiacal constellation Virgo. Five hours east of the meridian and 30 degrees south of it is the constellation Scorpio. Consequently, on this date and at this time of day Scorpio should be seen just rising in the southeastern sky. In this manner these maps can be used for any day in the year and any time of the day. The constellations and the maps together give one the means of locating any group of stars he wishes at any time whatever.

Naming the Stars. The brightest star in all the sky is called Sirius. There are also Vega, Aldebaran, Arcturus, etc. But since the number of stars visible to the unaided eye is about 5,000 and the number within the reach of our telescopes runs up into the millions, it is obvious that it would be a difficult problem to have names for all of them. As a matter of fact only a relatively small number have actually been given names.

One of the methods of designating the stars, besides giving them names, is by stating in what constellation they are to be found and their rank in the constellation in order of brightness. The brightest star in a constellation is called Alpha, a Greek letter, the second, Beta, etc. The name of the constellation is put after the Alpha, Beta, etc., in the genitive case. For example, according to this system of designating the stars the brightest star in the constellation Leo is called Alpha Leonis, and the brightest star in Cygnus (the Swan) is called Alpha Cygni. But since there are only 24 letters in the Greek alphabet it is obvious that this method has its limitations. After the Greek letters are exhausted the Roman letters are sometimes used. But the list of Roman letters is also limited, and in a constellation having thousands of stars this method is obviously entirely inadequate.

Another method, adopted by the English observer, Flamsteed, about 1700, is to number all the stars in each constellation according to their right ascension. Thus No. 1 in Leo would be that star in the Lion which is farthest west; that is, whose right ascension is the least. The objection to this method is that the numbering has no relation whatever to the magnitudes and depends upon a very arbitrary and irregular division of the whole sky into constellations. If, after a catalogue is made, new stars should be added, it would be necessary to re-number all of those which had a greater right ascension.

Still another method of designating the stars is to give their number in a certain catalogue irrespective of the constellation in which they appear. The stars in these catalogues are often arranged and numbered in the order of their right ascension. While this system has no relation to their magnitudes, it depends upon their positions in the sky and is convenient when one wishes to make an observing program. If a certain star will be visible on a certain evening at a convenient time for observation, then all of those whose numbers are near it will also be visible at the same time. The fact that they are north or south of it makes no important difference unless, indeed, they are so far south as to be always invisible.

Star Catalogues. The earliest star catalogue of which we have any record is a catalogue of 1,080 stars made by Hipparchus for the epoch 125 B. C. It was inspired by the appearance of what is called a temporary star. In a region of the sky in which no star had before that time been visible a brilliant star suddenly blazed out and after a few months disappeared. Hipparchus was astonished by the phenomenon since nearly all the stars are always the same. He determined then to make a catalogue of all the brightest stars, giving their positions in order that later astronomers might be able to determine whether they were appearing and disappearing and whether they were changing their positions in the sky. This catalogue of Hipparchus was revised and reduced to the epoch 150 A.D. by the astronomer Ptolemy.

Fig. 35. Photograph of a Part of the Constellation Taurus Showing the Hyades near the Top of the Picture

Tycho Brahe, who has been mentioned as being a great observer, in 1580 made a catalogue of 1,015 stars. Since that time star catalogues have been very numerous.

One of the greatest made by direct telescopic observations is that of Argelander (1799-1875) which contains 324,198 stars. While only about 5,000 stars are visible to the unaided eye, Argelander made his catalogue with a telescope 2.5 inches in diameter. There are many catalogues containing from a few hundred to a few thousand stars whose positions are given with the very highest degree of precision. They are useful in determining with great accuracy the positions of the heavenly bodies which move, such as the planets and comets; for it is only necessary to locate a wandering body with respect to the known fixed stars in order to have its position.

Recently an enormous catalogue made by another plan has been projected and nearly completed. It was found in 1882 that the stars could be photographed. This suggested to the English astronomer Gill the making of a catalogue of the whole sky by the photographic process. A photograph of a region is taken and on the photographic plate there will be the images of some stars whose positions are already known. When the distances and directions of the unknown stars from the known stars are measured, their positions become known. The work of making this great catalogue was undertaken by international co-operation and the work was divided among many observatories. Necessarily some photographs had to be taken from points on the earth north of its equator and others from places south of its equator. Each plate covers about four square degrees of sky, and since they must overlap in order to connect with one another, and since it is advisable to have the whole sky covered twice, nearly 22,000 plates are required. On these plates about 15,000,000 of stars will be shown. Many of them will be very faint and it is at present planned to measure and catalogue only 1,500,000 of them. Fig. 35 is a photograph of a region in the constellation Taurus and includes the stars known as the Hyades, which can be seen as a little cluster near the top of the picture.

Magnitudes of Stars. The quantity of light we receive from the different stars differs greatly, and probably we do not get precisely the same light in quantity and quality from any two stars. The magnitude of a star refers to the quantity of light we receive from it and has no necessary relation to its actual size or brilliance. A rather faint star near us would give us more light than a much larger one farther away. The stars which can be seen without the aid of a telescope are divided arbitrarily into six groups. The 20 brightest stars constitute the first group, and the average of the 20 brightest is the ideal first-magnitude star. The faintest stars that can be seen without a telescope are the sixth-magnitude group.

It is found by observations that a first-magnitude star gives us 100 times as much light as a sixth-magnitude star. Of course, what is a sixth-magnitude star depends somewhat upon the sensitiveness of the eye of the observer if it is defined as the faintest star which can be seen without a telescope. It also depends upon various other factors, such as the transparency of the atmosphere and the presence or absence of moonlight or artificial light. But those stars which are $\frac{1}{100}$ as bright as the ideal first-magnitude star are at least near the limits of visibility under ordinary conditions, and are taken as the stars of the sixth magnitude. If the ratio of light of the first-magnitude star to the sixth-magnitude star is as 100 to one, it is found in order that the ratios from the first to the second, the second to the third, and so on, shall all be equal, that the ratio of the light from a first-magnitude star to that from a second-magnitude star is as 2.512 to 1; and, in general, the ratio of the light received from any star to one in the next group fainter is this same number.

The stars next fainter than those which are visible without a telescope constitute the seventh-magnitude group. Then follow the eighth, ninth, and so on. The faintest stars which are in reach of our best modern instruments are of about the seventeenth magnitude.

If a star is brighter than the ideal first-magnitude star its magnitude is taken as less than one. For example, the star Vega, being brighter than the ideal first-magnitude star, has a magnitude 0.2; and the brightest star in the sky, Sirius, has a magnitude −1.4. In describing the magnitudes of the stars it is necessary to use decimals in order to attain a considerable degree of accuracy because the stars do not fall into the ideal groups. There are many between the exact first and the exact second magnitudes, and so on, for all other even magnitudes. The star Vega is brighter than the first-magnitude star but not a full magnitude brighter. Consequently, its magnitude is not 0.0, which would be a full magnitude brighter, but 0.2. The star Sirius is more than one magnitude brighter than Vega and going beyond the 0.0 has to be represented by a negative number. It is 2.4 magnitudes brighter than the ideal first-magnitude star. On this basis the magnitude of the sun is approximately −26.

TABLE II

List of First-Magnitude Stars

Star	Magnitude	Right Ascension	Declination	Color	When on Meridian at 8 P. M.
Sirius (Greater Dog)	−1.4	6 hr. 40 m.	−16° 34′	Bluish white	July 1
Arcturus (Boötes)	0.0	14 10	+19 48	Orange	Oct. 24
Vega (Lyra)	0.2	18 33	+38 40	Pale blue	Jan. 1
Capella (Auriga)	0.2	5 8	+45 52	Yellowish	June 6
Rigel (Orion)	0.3	5 9	− 8 20	White	June 6
Canopus (Argo)	0.4	6 21	−52 38	Bluish	June 26
Procyon (Smaller Dog)	0.5	7 33	+ 5 32	White	July 12
Betelgeuse (Orion)	0.9	5 49	+ 7 23	Ruddy	June 17
Alpha Centauri	1.0	14 31	−60 20	White	Oct. 28
Achernar (Eridanus)	1.0	1 33	−57 51	White	April 11
Altair (Aquila)	1.0	19 45	+ 8 33	Yellowish	Jan. 17
Aldebaran (Taurus)	1.0	4 30	+16 16	Red	May 28
Antares (Scorpio)	1.1	16 22	−26 10	Deep red	Nov. 27
Pollux (Gemini)	1.1	7 38	+28 19	Orange	July 15
Spica (Virgo)	1.2	13 19	−10 32	White	Oct. 11
Beta Centauri	1.2	13 55	−59 48	White	Oct. 20
Alpha Crucis	1.3	12 20	−62 26	Bluish white	Sept. 26
Fomalhaut (Piscis Australis)	1.3	22 52	−30 16	Ruddy	March 5
Regulus (Leo)	1.4	10 2	+12 33	White	Aug. 21
Deneb (Cygnus)	1.4	20 38	+44 53	White	Feb. 1

It is easy to get a general idea of the relative brightness of stars separated by any magnitude. Suppose, for example, we wish to find how much brighter stars of the first magnitude are than those of the seventeenth. As has been stated, stars of the first magnitude are 100 times brighter than those of the sixth; similarly, those of the sixth magnitude are 100 times brighter than those of the eleventh. Therefore, the stars of the first magnitude are $100^2 = 10,000$ times brighter than those of the eleventh. Those of the eleventh magnitude are 100 times brighter than those of the sixteenth. Consequently, the stars of the first magnitude are $10,000 \times 100 = 1,000,000$ times brighter than those of the sixteenth magnitude. Those of the sixteenth

TABLE III

Number of Stars Visible to Naked Eye

First magnitude	20	Fourth magnitude	425
Second magnitude	65	Fifth magnitude	1100
Third magnitude	190	Sixth magnitude	3200

magnitude are 2.5 times brighter than those of the seventeenth. Therefore, we have for the final result that stars of the first magnitude are 2,500,000 times brighter than those of the seventeenth. Those of the sixth magnitude are 25,000 times brighter than those of the seventeenth. These results give an idea of the relative power of our modern instruments compared to that of the unaided eye. Computing the relative brightness of the sun in the same way, we find, under the hypothesis that its magnitude is −26, that it is in round numbers 60,000,000,000 times brighter than the ideal first-magnitude star.

First-Magnitude Stars. The twenty stars that constitute the first-magnitude group are conspicuous objects in the heavens which always keep their positions relative to the others. They serve as guideposts for a study of the constellations, and those which are visible in the latitude of the observer should be familiar to him. They are distinguishable by their brightness, their color, and their relations to fainter stars near them. A table of the first-magnitude stars is given herewith, including also in the second column their magnitudes; in the third, their right ascensions; in the fourth, their declinations; in the fifth, their colors; and in the sixth, the times of year at which they cross the meridian at 8 P.M. The names of the constellations to which the stars belong are given in parenthesis under their proper names, except in those cases where the stars have no special names. From the principles which have been explained above, it is a relatively simple matter to find their approximate positions in the sky at any time and, by means of Table II, to locate them. When they have once been located and carefully observed for their own peculiarities and relations to neighboring stars, they will not be forgotten.

Number of Stars. It is a common impression that the stars which are visible to the unaided eye are absolutely numberless, and they are often compared to the grains of sand on the seashore. As

Fig. 36. Star Cloud in Sagittarius Photographed by Barnard

a matter of fact, they are not only finite in number, but their number is not very great. In Table III is given the number of stars in the whole sky in the first six magnitudes.

It is seen that the whole number of stars in all the sky visible without telescope is 5,000. At any one time fewer than half of these are visible because only one-half of the sky is above the horizon, and those faint stars whose light must come through the denser atmosphere near the horizon are not visible.

It will be noticed from Table III that each fainter magnitude has approximately three times as many stars as the preceding one. If this ratio continues it is found by calculation that there are about 200,000 stars in the first nine magnitudes, and the actual observations are in harmony with this computation. If the ratio kept up indefinitely there would be infinitely many stars. But beyond the ninth magnitude it begins to fall off, so that each fainter group has fewer than three times as many stars in it as are in the preceding group. It is not known with any high degree of accuracy how many stars there are in the first 17 magnitudes, which are within the range of the most powerful telescopes, but from counts of many representative regions it is concluded that there are probably more than 100,000,000 of them. Fig. 36 is a photograph of a portion of a part of the great star cloud in Sagittarius. This bright part of the Milky Way is in the southern sky in the early evening in mid-summer.

Proper Motions of Stars. The stars are called "fixed," and the fainter ones are the most nearly fixed of anything we know. Yet they are not absolutely fixed. They move slowly with respect to one another, and with accurate instruments it is possible in many cases to detect these changes in a relatively short time. The motions of the stars relatively to one another, or rather their motions with respect to the ideal, fixed right ascension and declination circles, are called their *proper motions*. The greatest proper motion known is only 8.7 seconds per year. Most of the stars move less than one second per century. The smallness of this greatest motion of 8.7 seconds per year is illustrated by the fact that it would take this star 220 years to travel over an arc equal to the apparent diameter of the moon. This star is of the eighth magnitude and is therefore invisible to the unaided eye. The proper motions of all visible stars are so small that the sky appears to us almost as it did to the ancient

Babylonians who first named the constellations. They looked up into the night sky and saw the Big Dipper, the Pleiades, Orion, etc., shining with almost the same luster as that with which these splendid stars shine at the present time, and situated relatively to one another sensibly as they are now.

The proper motions of the stars are, of course, due to their actual motions. The sun, being a star also, has an actual motion through space. It is moving nearly toward the star Vega at the rate of 400,000,000 miles per year, or at the rate of 12 miles per second. The motions of the stars toward us or from us are determined by means of the spectroscope. It is found from those which so far have been observed by means of the spectroscope (only those of the eighth magnitude or brighter), that on the average they move at the rate of about 20 miles per second, or about 700,000,000 miles per year. One might imagine at first thought that, if a star were coming toward us at the rate of 700,000,000 miles per year, or at the much greater rate at which some of the stars move, it would speedily become brighter, and that if it were receding, it would diminish in brilliance. The fact is, however, that their distances are so great that these changes do not alter their apparent magnitudes by sensible quantities in the course of the few centuries or, at the most, the few thousand years, they have been under observation.

The Milky Way or Galaxy. There is a band of hazy light, averaging about 20 degrees in width, stretching around the sky in approximately a great circle. A keen eye, under good circumstances, can see that it is made up, at least in its coarser parts, of fine stars, and it was commonly supposed by the ancient Greeks that it was a vast aggregation of stars so minute that they were not individually distinguishable. The Pawnee Indians of our western plains have the curious story that it is a cloud of dust made by a buffalo and horse racing across the sky. For a long distance it presents a lengthwise division. They thought the horse ran on one side, where the stars are a little larger, and kicked up a coarse dust; and that the buffalo ran on the other side and kicked up a fine dust, which constitutes the part whose individual stars are beyond visibility.

The Milky Way runs diagonally across the sky; that is, it does not follow an hour circle or a declination circle. It crosses the equator at points whose right ascensions are about 7 hours and 19

Fig. 37. Dark Lanes in the Star Clouds in Ophiuchus, Photographed by Barnard at the Yerkes Observatory

hours, and its inclination to the equator is about 63 degrees. The north pole of the Galaxy has a right ascension of about 13 hours and a declination of 27 degrees. It is extremely irregular in outline, having many dense star clouds and at other places dark holes and dark rifts across it. Fig. 37 is a photograph of a portion of the Milky Way in Ophiuchus, showing star clouds, nebulas, and dark lanes.

How to Find the Pole Star. The most conspicuous group of stars in the northern heavens which is always visible to observers of our latitude, is the Great Dipper. Everyone who knows any stars at all is familiar with this group. Its outline is perfectly definite and is made up of seven stars of about equal magnitude—the second. When the Dipper has been located it is easy to find the pole star. Start at the bottom of the bowl of the Dipper on the side opposite the handle, go along the edge of the Dipper opposite the side of the handle and continue about five times the distance between these two stars, and the pole star is reached. The two stars in the Dipper in the side opposite the handle are called the "Pointers," for they are almost exactly in a line with the pole star. Knowing this fact and the distance of the pole star from them compared to their distance apart, it is always easy to locate it. It is near no other bright star and is itself of the second magnitude. Since it is always visible in the northern hemisphere it serves as a unit for determining the magnitudes of stars whose brightness is approximately equal to that of itself.

In describing the positions of stars it is extremely convenient to say that one is in a certain direction and distant a certain number of degrees from a known star. Ordinarily, a person has a vague idea of the distance covered by 20 degrees on the sky, for he knows the whole circumference is divided into 360 degrees. Therefore, it is useful to have in mind a number of distances between stars for use as units. One convenient unit is the altitude of the pole star above the horizon. It was shown above that it is equal to the latitude of the observer. Consequently, if the observer's latitude were 40 degrees the altitude of the pole star would be 40 degrees. This gives a means of estimating distances of about 40 degrees. An error is likely to creep in because the distance from the horizon in a vertical direction from the pole star generally seems somewhat different from a distance of 40 degrees between two stars which are not on a vertical circle. The distance between the Pointers in the Big Dipper is approximately five degrees. This serves as a very convenient unit for measuring the small distances. The distance between the stars at the bottom of the Big Dipper is seven degrees. And the distance from the Pointer nearest the pole to the pole star is 28 degrees.

Fig. 38 gives an outline map of the Big Dipper and the pole star with the names of the stars. In this case the scheme of naming the brightest star in the constellation Alpha, the next brightest Beta, and so on, is not followed. The star Zeta at the bend in the handle of the Big Dipper, which was called Mizar by the Arabs, has a very faint star near it called Alcor, which means "the test." The Arabs considered the eyes of a person good if he could see this faint test star. The difficulties of seeing it are due to the fact that it is near the bright star Mizar and is itself faint. This star should be looked for and it will be found that every one can easily see it whose eyes are considered anywhere near normal.

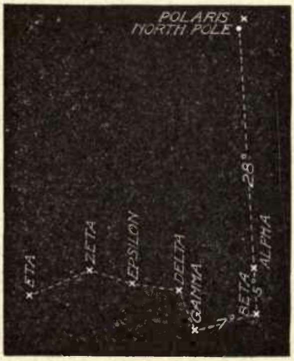


Fig. 38. The Big Dipper and the Pole Star

The star Alcor is of the fifth magnitude and its distance from Mizar is 11.5 minutes of arc. The shortest distance between two stars which are visible as distinct objects without telescopic aid, is about three minutes. With a telescope it is found that Mizar itself is a fine double, composed of a white star and one of an emerald color. The distance of the two components from each other is about 14.6 seconds of arc, and a 3-inch telescope will easily show them. It is not to be inferred that the two suns which compose this system are really very close together because they appear close together. This apparent nearness is the consequence of their vast distance from us. It is not known just how far they are away but almost certainly it takes their light more than 100 years to come to us. The meaning of this statement becomes apparent when one remembers that light travels at the rate of 186,330 miles per second.

The brighter component of Mizar was found to be a double by the use of the spectroscope in 1889. This discovery by Professor E. C. Pickering was the first of its kind. A spectroscopic binary is one in which the two components are so close and their distance from us so great that they are not visible as separate objects with any telescope. But by an adaptation of the spectroscope, whose description will be deferred, it is possible under certain circumstances to determine their binary character. Not only this, but in the case of the spectroscopic binaries it is possible to find out other things about the system, particularly the actual distance of the stars apart and their combined mass. In the case of the brighter component of Mizar the stars perform a revolution about their center of gravity in 20.5 days and are at a distance of 25,000,000 miles from each other. Their combined mass is about five times that of our sun.

The pole star is also an object of much interest. It is found to be a double star having a faint companion of the ninth magnitude at a distance from it of about 18.5 seconds. The component can be seen with a 5-inch telescope using a magnifying power of from 75 to 100 diameters. The larger one of the two components was found in 1899 to be a spectroscopic binary. This group of stars is so far from us that 40 years are required for its light to come to us; that is, we see it as it was 40 years ago.

Cassiopeia. The right ascension of this constellation is about zero hours. Consequently, it is on the meridian at 8 P. M. November 21. But if one wishes to find it without referring to its right ascension and declination it can be located by going from the Great Dipper through the North Star and as far beyond as that distance. It is, therefore, above the pole when the Dipper is directly below. Cassiopeia is distinguished by a zigzag, or letter *W*, composed of stars from the second to the fourth magnitude. The brightest star is at the bottom of the second part of the *W*. This is found to be a fine double star whose colors are rose and blue, and it can be seen separately with a 2-inch telescope.

One of the most interesting objects in the constellation of Cassiopeia is the star Eta, which is near the middle of the third stroke of the *W*, and about two degrees from the brightest star. It is a fine double star and can be separated with a 3-inch telescope. These two stars form a physical system and revolve around their center of gravity in a period of about 200 years. They are so far away that it takes their light about nine years to come to us.

In the constellation Cassiopeia a temporary star suddenly appeared in 1572. Its dazzling splendor and the fact that it had recently appeared, attracted the attention of Tycho Brahe who was then a young man, and turned his attention to astronomy.

The Equinoxes. It is possible to find the positions of the equinoxes by means of the processes described above, but it is also possible to locate them easily by direct observations of the stars.

To find the vernal equinox, draw a line from Polaris through the most westerly star in the *W* of Cassiopeia and prolong it 90 degrees. The point where it strikes the equator is the vernal equinox. The autumnal equinox is obtained by drawing a line from Polaris through Delta Ursæ Majoris and prolonging it until it strikes the equator. This point is in the constellation Virgo about 10 degrees north and 20 degrees west of the first-magnitude star Spica.

Lyra. Lyra (the Lyre) is a small constellation but one of the most interesting of them all. Its mean right ascension is about 18.7 hours and its declination is about +40 degrees. It is conspicuous because of the brilliant first-magnitude star Vega which is in it.

It was explained in connection with the discussion of the precession of the equinoxes, that the plane of the earth's equator slowly shifts on account of the attraction of the moon and sun on the earth's equatorial bulge. This causes the axis of the earth to point continually in different directions. The pole of the sky is the point on the celestial sphere toward which the axis of the earth is directed. On account of the precession of the equinoxes the position of the pole of the sky is continually changing. It describes a circle whose radius is 23.5 degrees and whose center is the pole of the ecliptic, in a period of 26,000 years. It happens that this circle which the celestial pole describes passes very near the star Vega. In 12,000 years from now the pole will be very near Vega and at this time that star will be the pole star. How much more glorious and conspicuous an object it will be than Polaris!

Lyra is also a constellation of interest because it is nearly in that direction that the sun with its planets is moving.

There are two stars of the fourth magnitude, Epsilon and Zeta Lyrae, each about two degrees from Vega. One is northeast and the other southeast, and with Vega they form a nearly equilateral triangle. The star Epsilon is a close double, composed of two nearly equal stars separated by a distance of 207 seconds of arc. It is a famous test object for observation without optical aid. A person with good eyes and under favorable atmospheric conditions in the absence of sky illumination can see the two components as separate objects. It is worthy of note that it never was known to be a double, so far as the records show, until after the invention of the telescope. If it is beyond the visibility of an observer he can usually see it with the aid of opera glasses. The object does not lose its interest when

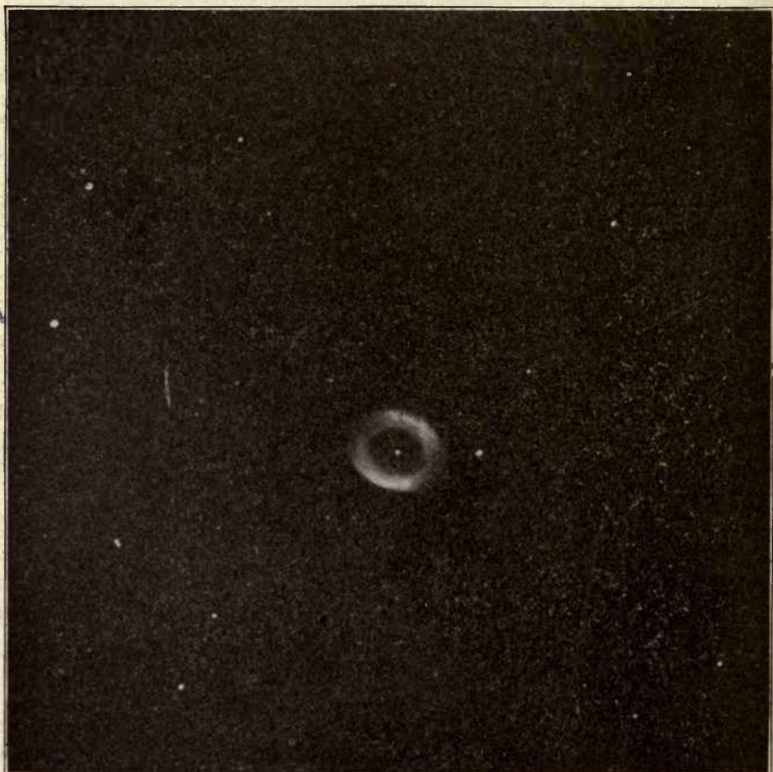


Fig. 39. The Ring Nebula in Lyra

viewed through a telescope. When examined under considerable optical power the two components, which are on the limits of visibility with the unaided eye, are seen to be very far apart, and each one of them is found itself to be a double. Thus, that which, at least at first glance, seems to be a single faint star in the sky, when examined with a powerful instrument, turns out to be a system of four magnificent suns.

Another interesting object in this constellation is the ring nebula. (See Fig. 39.)

Scorpio. Scorpio (the Scorpion) is the ninth zodiacal constellation and the most brilliant of all. In fact, it is one of the finest southern constellations that can be seen in our latitude. It is always easily recognized by the fiery red first-magnitude star Antares which

Fig. 40. The Great Star Cluster in Scorpio

in light-giving power is equal to 900 suns such as our own. About five degrees northwest of Antares is a very compact and fine cluster of stars in which about 5,000 of these objects are crowded in a region apparently one-fifth the size of the moon. (See Fig. 40.)

Boötes. Boötes (the Hunter) is a large constellation reaching from near the equator to within 35 degrees of the pole, and having a mean right ascension of about 15 hours. The most conspicuous object in it is the brilliant orange-colored, first magnitude star Arcturus. This star is approaching us at the rate of about five miles a second, but it is so far away that it takes its light 100 years to come to us. Its light-giving power is about 1,300 times that of our sun.

Leo. Leo (the Lion) is another one of the zodiacal constellations and the ecliptic passes very near to its brightest star, Regulus. It is about 60 degrees west of Arcturus and is easily recognized by a sickle of seven stars opening to the southwest, with Regulus at the

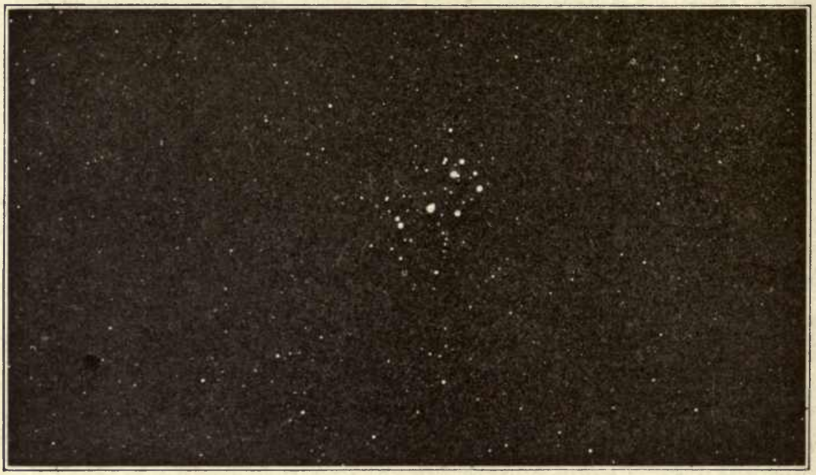


Fig. 41. Photograph or the Pleiades—the "Seven Sisters"—Made at the Yerkes Observatory

end of its handle. One of the many things of interest in connection with this constellation is that the November meteors seem to radiate from it.

Taurus. Taurus (the Bull) contains the Pleiades, the Hyades, and Aldebaran. The Pleiades include seven fourth-magnitude stars forming roughly a small dipper, and are mentioned in the sacred writings and the folk-lore stories of primitive peoples more often than any other group of stars in the sky. The ancient Greeks called them the "seven sisters" and had a story of how one was later lost. Apparently, those who wrote about them at that date were able to see only six. Now seven are easily visible to anyone of good eyesight under favorable conditions, and to those with more acute vision, under the best circumstances, ten or eleven are visible.

In Fig. 41 is given a photograph of the Pleiades together with many stars which can be seen only with optical aid. While the Pleiades appear to be small insignificant objects in the heavens they are, as a matter of fact, giant suns. Those brighter ones which can be seen without a telescope are from 200 to 300 times as great in light-giving power as our own sun. They are so far away that, according to the discussion of Newcomb, it takes their light 267 years to come to us. At one time a German astronomer, Mædler, supposed that Alcyone, the brightest star of this group, was in the center of the universe. This idea has been abandoned as there is no evidence whatever to support it. The ecliptic passes about four degrees south of the Pleiades. Consequently, the sun, moon, and planets pass near it, and in fact the moon sometimes eclipses these stars.

The Hyades are a large and diffuse group of stars which have been found by recent observations of Boss to be moving with about equal speed toward a distant point in the sky. This, of course, does not necessarily mean that they are going to collide in the remote future. But the parallelism of their motion and the equality of their speed shows that beyond question they have had a common origin. The examinations of them with the spectroscope, which is an instrument that enables us to determine the chemical constitution of luminous bodies, shows that these stars are very much alike in their constitution, a fact which also points to a common origin for them.

Orion. South of Taurus is the constellation Orion, lying across the equator between the fifth and sixth hours of right ascension. This is one of the finest regions in the whole heavens for a study without a telescope. In the winter months, in the early evening, it is seen in the southeastern and southern sky. In the northern part of it is the ruddy star Betelgeuse, and about 20 degrees southwest is the first-magnitude star Rigel. About midway between them and almost on the equator is a row of second-magnitude stars running northwest and southeast (in Fig. 42 these stars are a little above and to the left of the center), which constitutes the belt of Orion. From the southern end of this line of three stars are three fainter ones going off toward the southwest. These constitute the sword of Orion. Careful observation shows that the center of these three is a little fuzzy. It is, in fact, one of the most magnificent spectacles in the whole sky, the Orion nebula. Fig. 43 shows this splendid object as revealed by our most powerful photographic telescopes.

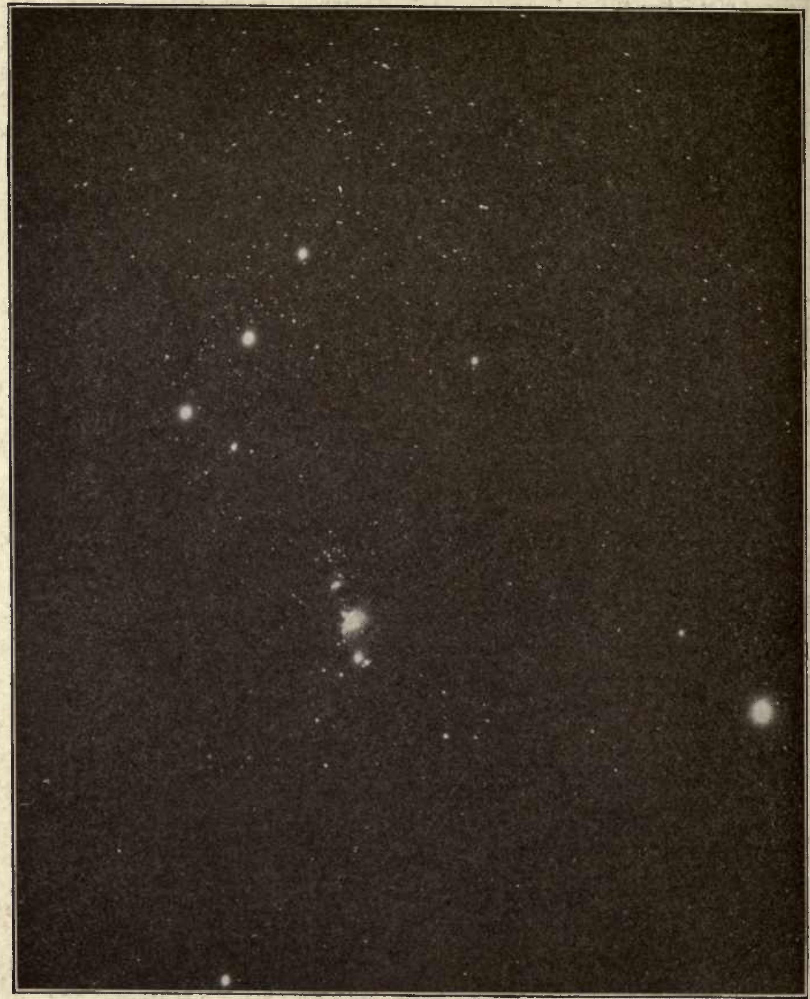


Fig. 42. The Belt and Sword of Orion and the Brilliant Rigel

The stars in this part of the sky are exceptionally large and remote from us. The star Rigel, shown at the right in Fig. 42, in light-giving power is equal to 10,000 such suns as ours.

Fig. 43 The Great Orion Nebula, Photographed at the Yerkes Observatory

Canis Major. Canis Major (the Greater Dog) is a constellation southeast of Orion and contains the brightest star in the whole sky, Sirius. The brightness of this star depends to a considerable extent upon the fact that it is relatively near to us. It takes the light from it 8.4 years to come to the earth. Expressed otherwise the star is 47,000,000,000,000 miles distant from us, and it is approaching us at the rate of about 10 miles per second. Sirius is really overtaking the sun, for the solar system is actually moving in almost exactly the opposite direction.

It was found in 1862 that the star Sirius had a very faint and distant companion. Observations since that time have shown that the two revolve around their common center of gravity in a period of about 50 years. The distance of the two components from each other is about 1,800,000,000 miles. A remarkable fact is that Sirius is 10,000 times as bright as its companion, while its mass is little more than twice that of its companion. Their combined mass is a little more than 3.5 times that of the sun, and they radiate about 30 times as much light as the sun.

Gemini. Gemini (the Twins) is the fourth zodiacal constellation and is noteworthy for its two principal stars, Castor and Pollux. In fact, the constellation gets its name from these two objects (twin stars), which are of nearly the same size and about 4.5 degrees apart. Castor is the one of the two which is farther north. In ancient times Castor seems to have been a little brighter than Pollux, but now the condition is reversed. This may be due to the fact that Castor is receding from us at the rate of 4.5 miles per second, while Pollux is approaching at the rate of 30 miles per second. With this large relative velocity of nearly 35 miles per second, over 2,000 years have been required for any conspicuous change in their relative brightness to take place.

TIME

Definition of Equal Intervals of Time. It is very difficult, if not impossible, to give a definition of time itself. So far as we, as thinking beings, are concerned, the amount of time which passes depends upon our intellectual activity in the interval. As an illustration, it may be mentioned that if we have many new intellectual experiences, as for example when we travel, the time seems long;

while when our activities are in their customary routine, time seems to speed rapidly. The same thing is illustrated by the well-known fact that a year seems much longer to a young person, to whom the experiences of the world are largely new, than it does to an older person, whose habits of life have become fixed and whose new experiences are not numerous. Clearly, however, it is impossible to define the length of time by means of the varying mental activities of any individual or group of individuals.

The first law of motion previously given states that a body subject to no force moves with uniform speed in a straight line. Therefore, by definition, it follows as a consequence of this law, or axiom, that *two intervals of time are equal if a body, subject to no force, passes over equal distances in them.* This is the definition of the equality of two intervals. In the long run it is found that our mental experiences are sensibly in harmony with it.

The difficulty in applying the definition to find out whether two intervals of time are equal, or what amounts to the same thing —the relation of two intervals—arises from the fact that it is practically impossible to find a moving body subject to no force and to bring it under observation. Because of this difficulty an indirect consequence of the laws of motion is used. It follows from them, as was explained above, that if the earth is subject to no exterior forces it will rotate with uniform speed. The character of the forces which modify its rate of rotation were discussed in connection with its rotation. It was seen that it rotates with sensibly uniform speed, and consequently it can be taken as the actual means of measuring intervals of time. Using the rotation of the earth as a measure, we agree that if the earth turns through equal angles in two intervals of time, then the two intervals are equal. The rotation of the earth makes the sky turn apparently from west to east. Consequently two intervals are equal if the sky, in its apparent motion, turns through equal angles in them. The rotation of the earth is the actual, fundamental means of measuring time, and clocks are regulated by it. The observations depend upon the stars and for this reason the discussion of this topic appropriately is taken up here after a discussion of the rotation of the earth and a description of the constellations.

Sidereal Time. Sidereal time is time measured by the rotation of the earth with respect to the stars; or, by the apparent motion of the stars around the earth. A sidereal day is the time it takes a meridian of the earth to move from a given position among the fixed stars around eastward to the same position again; or, thinking of the stars as moving, at least apparently, it is the interval required for the fixed stars to pass from the meridian around the earth and back to it again.

The sidereal day is divided into 24 sidereal hours, a sidereal hour into 60 sidereal minutes, and a sidereal minute into 60 sidereal seconds.

Solar Time. Our activities are largely regulated by the day and night. Consequently, time for practical purposes should depend upon the apparent motion of the sun around the earth rather than that of the stars. It is clear that since the sun moves eastward among the stars about one degree daily in its apparent annual motion around the heavens, the diurnal motions of the stars and sun are different. Solar time is time measured with reference to the sun. The solar day is the time it takes the meridian to pass from the sun eastward around to the sun again; or, the time it takes the sun to pass from the meridian apparently around westward back to the meridian again.

Solar days and sidereal days are not of equal length, the solar days being nearly four minutes longer. This is easily understood from the fact that the sun moves eastward among the stars. Suppose the meridian is in conjunction with the sun and certain stars, and that it moves eastward and around to the same stars again. This interval constitutes a sidereal day. In the meantime, however, the sun will have moved eastward about one degree and the meridian must overtake it before the end of the solar day. Therefore, the solar day is longer than the sidereal day, and the difference is the time it takes the earth to rotate about one degree. The earth rotates 360 degrees in 24 hours, or 15 degrees in one hour. Therefore, it will rotate one degree in one fifteenth of an hour, or in four minutes. That is, the solar day is about four minutes longer than the sidereal day.

In Fig. 44, let S represent the sun and E_1 the position of the earth at one time. Consider the meridian m, which is on the side toward the sun, and the distant star s. Suppose that in one sidereal day the earth moves forward to E_2 (of course, the distance traveled is greatly exaggerated in the figure). This means that the meridian *m* is on the side toward the star again. It is clear from the figure that the earth must turn through the angle *a* which is equal to the angle which it has moved forward in its orbit, in order to bring *m* in line with the sun. This shows why the solar day is longer than the sidereal day.

Mean Solar Time. It has been stated above that the sidereal days are all of the same length and that the solar days are longer than the sidereal because of the earth's motion forward in its orbit. If the axis of the earth were perpendicular to the plane of its orbit and if the earth moved forward in its orbit at a uniform speed, the differences between the sidereal and solar days would all be the same. That is, the solar days would also all be of the same length. But the earth's orbit is an ellipse and it moves in such a way that the law of areas is fulfilled. When it is near the sun it moves over a

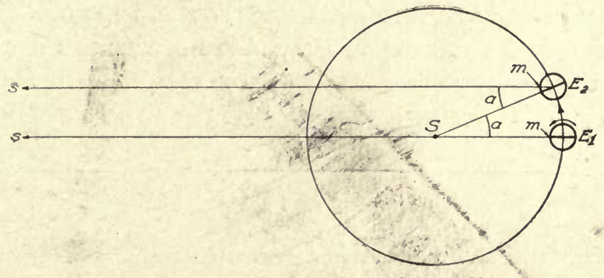


Fig. 44. The Solar Days Are about 4 Minutes Longer Than the Sidereal Days Because the Earth Revolves around the Sun

greater angular distance in a given time than when it is far from it. It follows from this that the solar days are longest—at least so far as this factor affects them—when the earth is near the sun. At present the earth is nearest the sun in our winter and farthest from it in our summer. Therefore, the solar days measured from noon to noon are longer in the winter than they are in the summer of the northern hemisphere.

There is another reason why the solar days vary in length. This is because the sun's apparent motion eastward in the sky is not along the equator but along the ecliptic. The difference in length between the sidereal and solar days depends upon the distance the sun moves eastward along the equator. Now, let us suppose for the sake of simplicity that the earth's orbit is a circle and that the earth moves uniformly along its circumference. In this case the sun will seem to move uniformly along the ecliptic. But let us assume that the ecliptic is inclined to the equator by 23.5 degrees, as is actually the case. In Fig. 45, the straight line represents the equator as it would be obtained by spreading the celestial sphere out on a plane. The ecliptic intersects it at the vernal equinox, *V*, and at the autumnal equinox, *A*. At *V* a considerable fraction of the sun's apparent motion is northward, and at *A* southward. Consequently, at these points its motion eastward along the equator is less than the average. But when the sun is at the summer solstice, *S*, and at the winter solstice, *W*, its motion is entirely eastward and along the small circles, viz, along those declination circles, respectively, 23.5 degrees north and south of the equator. At these points it moves eastward faster than the average.

Since the excess in length of the solar day over the sidereal depends upon the eastward motion of the sun, it follows that so far as the causes now under consideration are concerned the solar days

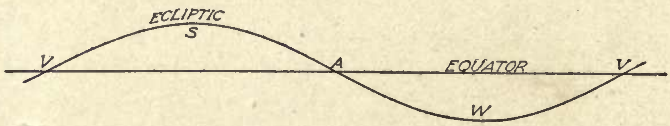


Fig. 45. The Sun Moves Eastward Along the Ecliptic Causing a Variation in the Lengths of the Solar Days

are shortest when the sun is at *V* and *A*, and longest when the sun is at *S* and *W*. The sun is at *V* on March 21, at *A* on September 23, at *S* on June 22, and at *W* on December 21. So far as this cause is concerned, the longest days are in the summer and the winter and the shortest in the spring and autumn.

The actual result is a combination of these two factors which influence the length of the solar day. On December 22 the solar day is 4 minutes and 26.5 seconds longer than the sidereal day when expressed in sidereal time. The solar days then steadily decrease until March 26, when the solar day is only three minutes and 38 seconds longer than the sidereal day. Then they increase in length until June 20, which is 4 minutes and 9.5 seconds longer than the sidereal day. From June 20 the solar days again decrease in length until September 17, which is the shortest day of the whole year, and is only 3 minutes and 35.2 seconds longer than the sidereal day. They then increase until December 22. The difference in length between the longest and shortest day in the year is therefore about 51.3 seconds of sidereal time.

The differences in the lengths of the solar days are not very great and it might be supposed that they could be neglected. But nowadays the best clocks are made to run so accurately that they much more than reveal this difference, and besides the difference accumulates. Consequently, it is not practicable to use the solar day. This leads to a definition of what is called *mean solar time. The mean solar day is the average of all the true solar days in the year.* In sidereal time its length is 24 hours, 3 minutes and 56.556 seconds It is divided into 24 mean solar hours, an hour into 60 mean solar minutes, and a minute into 60 mean solar seconds. This is the actual day in ordinary use.

Standard Time. Each meridian on the earth has its own time because the sun crosses each meridian at a separate time. Therefore, if we were to use mean solar time only those places which are on the same meridian would have the same time. It is clear that very great confusion would result from this. It was stated above that a degree of longitude at latitude 40° is about 53 miles. That is, at our latitude there is a difference of four minutes in mean solar time for every 53 miles, or one minute for every 13 miles. While for many purposes so slight a variation as this would not be important, yet in the running of trains and boats it would be of the highest importance. This is especially true in a country where most of the great trunk lines of railways run in an easterly and westerly direction.

In order to avoid the confusion resulting from each meridian having its own time the railways, in 1885, by common agreement, adopted the same time for a strip of country between meridians about 15 degrees apart. The hour adopted was the correct mean solar time for the meridian approximately through the center of the strip. Therefore, the error on each side increases to about one-half an hour at the extremity of the strip. Since one degree is about 53 miles in our latitude, the width of these strips averages about 800 miles. For convenience the strips are not of uniform width and do not strictly follow the meridians. It is clear that it would be inconvenient for a railway system to change time except at one of the divisions of the road. Therefore, the place of the change of time is made to agree with the ends of divisions on the railway. The accompanying map, Fig. 46, shows the time zones in the United States.

The easternmost division is called eastern time, and has the time of the meridian which is 75 degrees west of the Greenwich Observatory. This meridian runs through Philadelphia. Next comes central time, the mean solar time of the 90th meridian west of Greenwich, which runs through St. Louis. Then follows mountain time, the time of the 105th meridian, which passes near Denver; and on the Pacific Coast they use the mean solar time of the 120th meridian, called Pacific time. This meridian passes about 100 miles east of San Francisco.

Fig. 46. The Standard Time Divisions in the United States

The difference between standard time and mean solar time can be calculated when one knows his distance from the fundamental time meridian of his zone, because 13 miles corresponds to a difference of about one minute.

If one is east of the fundamental meridian the sun crosses his meridian before it does that of the fundamental meridian. Consequently, by the sun the time is later than it is by standard time. That is, he would say that standard time is slow. For example, Chicago is about 100 miles east of the meridian through St. Louis, and therefore standard time at Chicago is about eight minutes slow. West of the meridian standard time is fast.

Civil and Astronomical Days. The civil day begins at midnight and ends at midnight mean solar time. It is clear that it is most convenient to have the date change when there are the least activities, especially in the business world, and the midnight change satisfies these conditions with sufficient accuracy.

The astronomical day, on the other hand, begins at noon and ends at noon, mean solar time. The reason for this is that it is most convenient to have the astronomical day change when fewest astronomical observations are made. About the only ones that can be made at noon are those of the sun.

Place of Change of Date. Suppose one should start at any place and go around the earth in a westward direction. On each day of his travel the sun would cross his meridian later than if he had stayed at home. In making the full circuit he would lose in this fashion exactly one day. But if he should go around the earth in the other direction the sun would cross his meridian earlier each day than if he had stayed at home, and the number of days measured by the number of times the sun crossed his meridian would be one greater than if he had not made the journey. It is clear from this that if one goes around the earth in the westward direction he must drop one day from his reckoning in order to be in harmony with those who have not made the journey, and if he goes eastward he must add one day to preserve harmony. It is convenient to have the place of the change of day a fixed one which is well agreed upon. It is also obvious that it is convenient to have this where there are few inhabitants, for one can see the confusion which would arise if on one side of the line through a populous district, as for example a large city, people had one day and date and on the other side a day and date differing by one day.

The place where the date is changed is about 180 degrees from the meridian of Greenwich. This passes through the Pacific Ocean and near very few land areas. There is no meridian in the whole earth that would cause less confusion. However, the change is not made precisely at the 180th meridian throughout its length. People who settled certain islands along this meridian going eastward from Europe naturally took their day and date with them, while those going in the other direction also took their day and date. These disagreed by one day when they met in the Pacific Ocean. On this account there are certain irregularities which are exhibited in Fig. 47.

The Sidereal Year. Just as there are different kinds of days depending upon whether we consider the rotation of the earth with respect to the stars or sun, so there are different kinds of years. The period of revolution of the earth with respect to the stars is called the sidereal year. It is the time required for the sun to pass apparently from any position among the stars back to the same position

Fig. 47. The Line at Which Travelers Change Their Day and Date, Dropping a Day If Going Westward and Adding a Day If Going Eastward

again. In mean solar time the length of the sidereal year is 365 days, 6 hours, 9 minutes, and 8.97 seconds, or just a little more than 365.25 days.

The Tropical Year. The tropical year is the time it takes the earth to move from the vernal equinox around to the vernal equinox again. Since the equinoxes have a precession, this year is a little shorter than the sidereal year. In mean solar time its actual length is 365 days, 5 hours, 45 minutes, and 45.51 seconds. Thus it is seen to be about 20 minutes shorter than the sidereal year. In order to keep the calendar fixed with respect to the seasons it is necessary to use the tropical year. As a matter of fact, this is the year in ordinary use rather than the sidereal year.

The Calendar. In very ancient times the calendar was largely based on the motions of the moon, which determined the times of religious ceremonies. The sun has the same appearance from day to day and probably was regarded as somewhat commonplace. The moon goes through an interesting and striking change of phases, which recur frequently enough so that they are easily remembered, and the fact that they systematically repeat was easily discovered. It was natural to define time by the phases of the moon, which continually vary but constantly recur.

When, however, records were kept over longer intervals of time it was found that the method was not a very convenient one. In the first place there is not an integral number of months in the year, the number being between twelve and thirteen. Therefore, a calendar based on the months has the seasons continually shifting with respect to it. The calendar of the ancient Egyptians was of this character. As the science of astronomy was developed they gradually turned to a calendar based on the year as a fundamental unit, and left the month largely out of consideration. In the year 46 B. C. the Roman calendar was reformed by Julius Caesar with the assistance of the Alexandrian astronomer Sosigenes. This calendar which is known as the Julian calendar, was entirely independent of the moon, and the year consisted of 365 days, with a leap year every fourth year of 366 days. The extra day was added at the end of February. This mode of reckoning makes the average year exactly 365.25 days. It is seen from the result given above that the length of the tropical year is about eleven minutes shorter than this. It follows from this that the Julian calendar falls one day behind in the course of 128 years. By 1582 the calendar was in error more than 12 days and the matter was getting serious. In that year Pope Gregory XIII introduced a slight change. Twelve days were omitted from that year and it was agreed that thereafter three leap years out of every four centuries should henceforth be omitted. This rule again is not quite exact, for the Julian calendar falls behind three days in $3 \times 128 = 384$ years instead of 400 years. Yet the error does not amount to a day until after more than 3,000 years have elapsed.

Although the Gregorian calendar is sufficiently accurate for 3,000 years, it will some time have to be still further corrected.

The rule for the leap year is very simple. All years whose date numbers are not divisible by 4 are years of 365 days. Those years whose date numbers are divisible by 4 are leap years unless they are also exactly divisible by 100. Those years whose date numbers are divisible by 100 are not leap years unless they are exactly divisible by 400, then they are leap years. This is as far as the rule has been extended up to the present time.

While the Gregorian calendar, or at least a slight modification of it, keeps the seasons fixed with respect to the year, yet it is in many ways imperfect. It is certainly inconvenient to have months of different lengths, to have the months in different years begin on different days of the week, and to have our numerous holidays and festival days, for this reason, continually shifting through the week. There are exceptions, of course, in those which are fixed on certain days irrespective of the date, as for example Easter and Thanksgiving. Recently suggestions have been made for the improvement of the calendar.

THE MOON

The Moon's Apparent Motion among the Stars. The standard method of determining the real motions of a heavenly body is *first* to get its apparent motions from the actual observations; and *second,* to get indirectly its real motions. The moon apparently moves eastward among the stars, completing a circuit of the sky in a little less than a month. Its apparent orbit is a great circle on the celestial sphere, though it does not coincide with the equator. It is near the ecliptic, deviating from it by only five degrees, nine minutes. When the moon is in that part of its orbit where the ecliptic is north of the equator it crosses the meridian in its diurnal motion high in the sky, and when it is at that part of its orbit where the ecliptic is south of the equator it crosses the meridian in its diurnal motion low in the sky. Since it makes the complete circuit of its orbit in a month, there are times each month when it crosses the meridian high and others when it crosses it low. When it crosses the meridian high it rises in the northeast and sets in the northwest, just as the sun rises in the northeast in the summer time and sets in the northwest. When it crosses the meridian at a low altitude it rises in the southeast and sets in the southwest, as the sun does in the winter time.

The period of revolution of the moon around the earth can be determined by its motion with respect to the stars or its motion with respect to the sun. The time it takes the moon to go from a certain place among the stars around the sky back to the same place again is called the *sidereal month.* It is found from the observations that its length is 27 days, 7 hours, 43 minutes, and 11.55 seconds. The time it takes it to go around the sky with respect to the sun is called the *synodic month.* This is clearly longer than the sidereal month, for if the moon were at one time in conjunction with the sun and certain stars and then moved eastward around the sky back to the same stars again, the sun in the meantime (27.3 days) would have moved eastward about 27 degrees. The synodic month then is longer than the sidereal by the time it takes the moon to move over this distance eastward and to overtake the sun. Since the moon makes a circuit of the heavens in 27 days, it follows that its eastward motion is on the average about 13 degrees a day. Consequently it will take it a little more than two days to overtake the sun after it has arrived back at the same stars again. That is, the synodic month is a little more than two days longer than the sidereal month. It is found from the observations that the length of the sidereal month is 29 days, 12 hours, 44 minutes, and 2.86 seconds.

The Moon's Phases. The moon shines only by reflected light and its phases as seen from the earth depend upon its position relative to the earth and sun. Where the sun's rays do not illuminate it, it is dark the same as the earth is on its night side. Fig. 48 shows the reason of the phases. In this figure the sun's rays come in from the right toward the left in sensibly parallel lines. The right side of the earth is the day side, and similarly the right side of the moon is the day side of the moon. When the moon is at M_1 the side toward the earth is the dark side and the phase is called the *new* moon. The appearance of it is indicated in N_1. In about a week the moon passes forward in its orbit in the direction indicated by the arrow to the point M_2. At this time half of the illuminated portion is visible to the earth and its appearance is indicated in N_2. This is at the *first quarter* and the moon is at the half-moon phase. In another week it moves forward to M_3, when the illuminated side is toward the earth and it appears as N_3. At the third quarter the moon is at M_4, and has the appearance of N_4.

Let us consider the matter a little more carefully. Suppose the earth rotates in the direction indicated by the arrow. Then as the observer passes from the day side of the earth to the night side he is at O at sunset. If he observes the new moon at sunset it will be in the same direction as the sun, or in the western sky. At the time of half-moon at the first quarter when the sun is in the western sky, it is seen from the diagram that the moon is on the observer's meridian and the light side of it is toward the west. When the moon is full the observer sees the sun setting in the west and the full moon

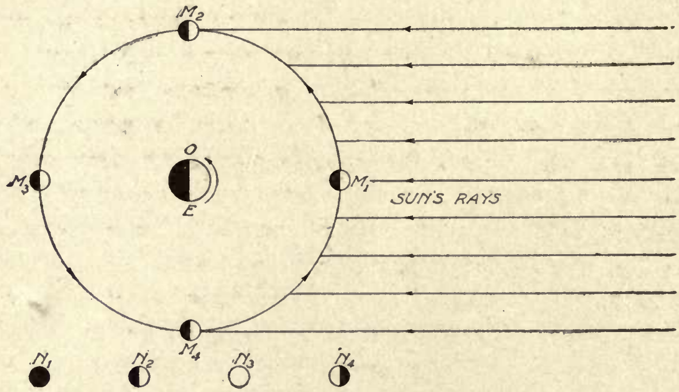


Fig. 48. The Reason for the Moon's Phases

rising in the east. Everyone knows that these results are in perfect harmony with the facts of observation.

When the moon is nearly new, that is, when it is between M_1 and M_2, it presents a thin crescent, convex toward the western sky. At this time, however, the rest of it can be dimly seen. It is clear from a study of the diagram that the earth has phases as seen from the moon similar to those of the moon as seen from the earth, the only difference being that they are opposite. That is, when the moon is new, as seen from the earth, the earth is full as seen from the moon. When the moon is in the position under consideration and nearly new the earth as seen from it is nearly full. Consequently, the moon is to some extent illuminated by the light that goes to it from the earth. The darker part of the moon that we see faintly when it is at this phase, is illuminated to a slight extent by the earth-shine. This earth-shine is about 20 times full moonlight.

Distribution of Sunlight and Moonlight. The amount of light received from the moon by the earth is of little importance except at the time of full moon. It follows from the preceding section that the full moon is exactly opposite the sun in the sky. Consequently, when the moon is nearly full it is above the horizon at night while the sun is below it, and is below the horizon while the sun is above. Because of this fact the light is more equally distributed throughout the 24 hours than it would be if they were both on the same side of the earth at this phase. This is not only true, but, since the full moon is opposite the sun in the sky, when the sun is at the part of the ecliptic south of the equator, the full moon is at the part of the ecliptic north of the equator. This means that at that time of the year, viz, the winter, when we receive the least sunlight, we receive the most moonlight, and in the summer when we receive the most sunlight, we receive the least moonlight. Everyone has the dim impression that the moon shines more brightly in the winter than in the summer, and such is a fact, as this discussion shows. Also, in the winter the full moon rises far in the northeast and in the summer in the southeast. Year after year it is almost exactly the same and no changes in the weather conditions can be ascribed to the changing relations of the moon relatively to the sun and earth.

The polar regions of the earth are conceived of as being places of perpetual darkness and desolation for six months each year. This conception is slightly in error, because after the sun has actually set there is a considerable interval in which the twilight is strong enough to enable men to carry on all ordinary pursuits. Also, since when the sun is below the horizon it is far south, the full moon is correspondingly north of the equator and is above the horizon. Therefore, for half of the dark period the moon between the first and third quarters circulates in the sky and lights up the surface of the earth. It follows from this that the long night in the polar regions is not quite so gloomy as it is often pictured.

Distance of the Moon. In order to determine the size and character of the moon, and also the character of its orbit, it is necessary to know its distance. The method of finding the distance of the moon is similar to that used by surveyors in finding the distance across an impassable gulf or chasm. Suppose the wavy lines in Fig. 49 represent the banks of an impassabie chasm, and that a surveyor wishes to know accurately the distance from *B* to *M*. He takes a point *A* on the bank of the chasm which is visible from both *B* and *M*, and then to the left on the bank lays down the lines *DA* and *CB* in such a way that *DC* shall be parallel to *AB*. He then draws a line from *A* to *E* parallel to *BC*. He measures the distances *AB*, *DE*, and *EA*. Since by construction the triangle *AMB* is similar to *DAE*, he has the proportion $BM : BA = EA : ED$, which solved gives $BM = (BA \times EA) \div ED$. It is clear from this that the distance across the impassable chasm can be measured as accurately as the distances *BA*, *EA*, and *ED* are measured on the level land.

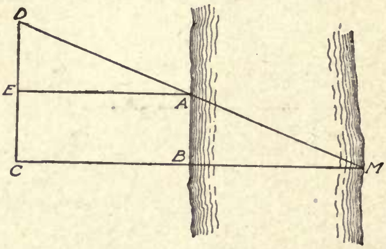


Fig. 49. Measurement of the Distance across an Impassable Chasm

As a matter of fact the measurement can be made a little more simply than has been described. The method is to set up at *B* a surveyor's instrument, which consists of a telescope that can be turned horizontally and which has degrees marked off indicating the direction at which it is pointed. After the telescope is accurately adjusted it is pointed at *M* and then turned and pointed at *A*. The readings of the circle at the two different times give the angle *MBA*. Then the instrument is set up at *A* and pointed at *M* and then at *B*. The readings in this case give the angle *MAB*. Now the distance *AB* is measured. Then, in the triangle *MBA*, the angles *A* and *B* and the included side are known. It follows from plane geometry that the triangle is determined by these three parts. Trigonometry enables one to compute the remaining sides when these three are given. Therefore, by trigonometry, which is based on such considerations fundamentally as the measurements of *DEA* described above, the distance *BM* can be computed.

In Fig. 50, let the circle *E* represent the earth and suppose *A* is the position of an observer in the northern hemisphere. The line *AZ* points to his zenith. Suppose the moon is on his meridian;

therefore, it will be to the south. He has a telescope set up at A fixed so that it can move in the plane of the meridian. It is pointed up at Z and then turned over until it points to the moon M. The readings of a circle similar to that on the surveyor's instrument give the angle ZAM. By subtraction the interior angle MAB can be found. Suppose there is another observer on the same meridian in the southern hemisphere at B. His zenith is in the direction BZ'. He sets up a telescope and measures the corresponding angle. Now consider the triangle MAB. The angle at A and the angle at B are known by the measurements, and since the observer at A knows how far he is north of the equator and the one at B how far he is

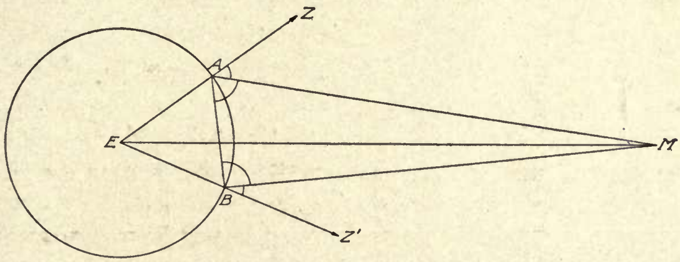


Fig. 50. Measurement of the Distance to the Moon by Observations from Two Points on the Earth's Surface

south of the equator, and since the size of the earth is known, the straight line AB is also known. Consequently, in the triangle we have given two angles and the included side, and the triangle can be solved precisely as in the case of the surveyor finding the distance across the chasm. This, fundamentally, is the way the distance from the earth to the moon is found. It must be understood that in carrying out the measurements many artifices are used to secure results of the highest order of accuracy. The point insisted on here is that the result is in no sense whatever guess-work, but that it is based upon careful measurements, and is in reality a measurement as much as is the measurement of any distance on the surface of the earth. The percentage of error in our knowledge of the distance of the moon from the earth is actually much less than the percentage of error of any of the ordinary distances we know on the earth. For example, it is rarely that the officials of a railway know the length of its track between two cities with the same relative degree of accuracy that astronomers know the distance from the earth to the moon.

It is observed that the measurement of the distance from the earth to the moon depends upon the measurements of two angles and the line joining two places, *A* and *B*. Our knowledge of the length of this line depends upon knowing the size of the earth. If there are any errors in our knowledge of the earth's dimensions they introduce corresponding errors in our knowledge of the distance from the earth to the moon. If, for some reason, we have obtained too large a diameter for the earth then the distance to the moon will be too large by the same factor. At the present time so many measurements of arcs on the earth have been made that we know its size with a very high degree of precision.

From the methods just explained it has been found that the mean distance from the earth to the moon is 238,840 miles. This distance is about ten times as far as around the earth. One who has traveled over any considerable portion of the earth's surface knows how great it is. We can get a mental picture of it by calculating how long it would take objects traveling with known speed to go

Fig. 51. The Earth and Moon and Their Distance Apart on the Same Scale

over so great a distance. It is known that sound travels with a high velocity. The puff of smoke from a gun is seen and almost immediately the report is heard. Or, perhaps better, a flash of lightning is seen in the sky and in only a few seconds the report of the thunder is heard. It is found from observations and experiments that sound travels a mile in about five seconds, or at the rate of 720 miles an hour. It follows from this and the distance to the moon that, if there were an explosion on the moon and the sound of it could come to us, it would require 14 of our days and nights to reach us. Of course, sound can not come from the moon to the earth because the atmosphere does not extend over that distance. In Fig. 51 the earth and distance to the moon are shown to a relative scale and on this figure the depth of the atmosphere, supposing it to be 100 miles, would be only $\frac{1}{600}$ of an inch.

If a train could come from the moon to the earth running at the rate of a mile a minute, night and day, without any stops whatever, it would require 166 days for it to come to us. These calculations give a better conception than mere figures of the great distance to the moon.

The Moon's Actual Motion. It follows from the moon's apparent motions and its distance that it moves around the earth in an orbit whose circumference is about 1,500,680 miles. Dividing this by the sidereal period, it is found that the moon's orbital velocity averages about 2,290 miles per hour, or 3,357 feet per second. It is found from the observations of the apparent diameter of the moon that its distance from the earth varies somewhat. Plotting its orbit by the method used in determining the shape of the earth's orbit around the sun, it is found that the moon's path is also elliptical and that the earth is at one of its foci. It does not move uniformly in its orbit, but moves in such a way that the radius from the center of the earth to it sweeps over areas which are proportional to the time.

The moon is carried forward with the earth in its motion around the sun. The motion of the earth is about 50 times as fast as that of

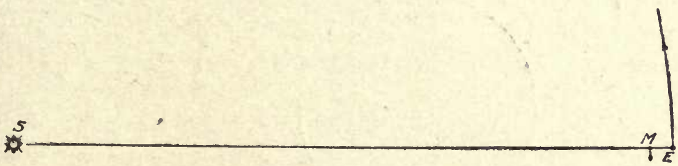


Fig. 52. The Motion of the Moon Relative to the Sun

the moon in its orbit. Consequently, when the moon is between the earth and sun, as at *M* in Fig. 52, and its motion is backward with respect to the earth, it is actually moving forward very fast with respect to the sun. The distance from the earth to the moon is about $\frac{1}{400}$ of the distance from the earth to the sun. It follows from this that the motion of the moon toward the sun and away from it, as it crosses the earth's orbit, is relatively insignificant compared to its motion forward as it is taken with the earth around the sun. The consequence of this is that the moon's orbit is concave toward the sun at every point and sensibly like that of the earth.

Up to this point we have spoken as though the earth moved around the sun in an elliptical orbit. As a matter of fact, it is the center of gravity of the earth and moon which describes this curve, these two bodies revolving around their center of gravity in a month. This point is only 3,000 miles from the center of the earth, and is therefore in round numbers 1,000 miles below its surface.

The moon always keeps the same face toward the earth. Consequently it rotates on its axis once while it passes around the earth; that is, its period of rotation is the same as that of its revolution. In Fig. 48 the side of the moon which is toward the left when the moon is at M_1 has turned around so that it is toward the right when the moon is at M_3.

Size of the Moon. The mean apparent diameter of the moon is 31 minutes 8 seconds, the apparent diameter varying by a little more than two minutes because of the eccentricity of the moon's orbit. When the apparent size of an object is known and its distance from the observer is known, it is a simple matter by trigonometry to compute its actual size. It turns out that the actual diameter of the moon is 2,163 miles. This result is known with the same degree of certainty as the distance to the moon. The diameter of the moon is about 27 per cent of that of the earth, and their relative dimensions are shown to the same scale in Fig. 53.

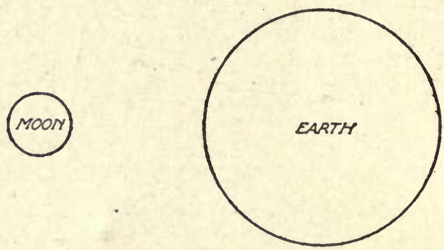


Fig. 53. The Earth and Moon Shown on the Small Scale

Since the surfaces of similar bodies are as the squares of their dimensions the surface of the moon is about $\frac{1}{14}$ that of the earth; and since their volumes are as the cubes of their dimensions the volume of the moon is about $\frac{1}{50}$ that of the earth.

When the moon is on the observer's meridian it is nearer the observer than when it is on his horizon by about 4,000 miles. Thus, in Fig. 54, O is about 4,000 miles nearer M than P is. Therefore, the moon ought to look larger when it is near the meridian than when it is at the horizon. As a matter of actual fact it is found by measurement with a telescope that the moon is apparently larger near the meridian than when it is on the horizon and the difference is in harmony with these figures. But without an instrument the moon certainly appears larger at the horizon. The explanation of this peculiar appearance, which is directly opposed to the actual facts, is that when the moon is high in the sky there is nothing with which to compare its distance, and the observer underestimates greatly its distance from us. Our judgment of the size of an object depends upon two things, its apparent diameter and our knowledge of its distance from us. If we think it is very close we unconsciously esti-

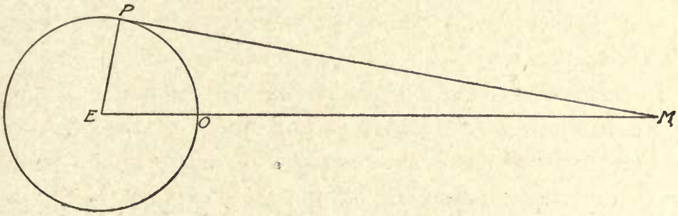


Fig. 54. Diagram Illustrating Change of Size of Moon

mate it as being of small size, while if we think of it as being very far away we judge that it is large. It is not difficult to bring a spider web near the eye and to force into the consciousness a belief, *first,* that it is something very near when it appears very small, as it actually is; and *second,* that it is something very far away when it has the appearance of a large cable, instead of a very minute thread. Now our estimate of the real size of the moon, or any other celestial object, depends in a similar way upon our unconscious estimate of its distance. As has been said, for some reason when the moon is high in the sky we judge that it is near to us, and consequently it appears small. When it is near the horizon it is easy to see that it is beyond the buildings and trees which are visible in its direction, and that forces into our consciousness the knowledge that it is far away. Then unconsciously we picture it as large. The actual measurements with instruments prove that the estimate that the moon is larger when near the horizon than when high in the sky, is purely subjective, and the explanation for this has just been given.

Mass of the Moon. The mass of the moon relatively to that of the earth is determined by the distance of the earth from the center of gravity of the earth and moon. The principle is the same as that of balancing weights on the arms of a lever. In Fig. 55 let W and w represent two weights at distances L and l from the fulcrum F. Then by the principle of the lever $W \times L = w \times l$. And so in the case of the earth and moon, the mass of the earth times

Fig. 55. Weighing the Moon

the distance from its center to the center of gravity of the earth and the moon equals the mass of the moon times its distance from the center of gravity of the earth and moon. The center of gravity of the earth and moon being determined from the observations of the motion of the earth around the sun, which determine the point describing the elliptical orbit, it is possible to find the mass of the moon in terms of the mass of the earth. It turns out that the mass of the earth is 81.7 times that of the moon. It follows from the volume of the moon given above, and the density of the earth given in the description of the earth, that the density of the moon is 3.4 times that of water.

The weight of a body on the surface of the earth depends upon the mass of the earth and the distance of the surface of the earth from its center. In particular, the weight of a body is directly proportional to the mass of the earth, and inversely proportional to the square of its distance from the center of the earth. The corresponding thing is true on the moon. Using the mass of the moon and the size of it given above, it is found that an object on the surface of the moon weighs only *one-sixth* as much as the same object would on the surface of the earth. This refers to weighing on a spring balance. If the object were weighed with an ordinary balance scale, where a small weight is used to balance the body weighed it would, of course, weigh the same as on the earth, because the change in pull on the body weighed and the balancing weight would be in the same ratio. It follows from the fact that a body weighs only one-sixth as much on the moon as it would upon the earth, that the same force there would throw it six times as high. If a man can jump five feet high upon the earth, the same man on the moon, if he could live there and exert the same energy, could jump 30 feet high. Volcanic activity on the moon would throw matter six times as high as the same activity on the earth. Since matter weighs less on the moon, mountains could be piled six times as high before the rock would crush and break out at their bottoms. Perhaps this partly explains why mountains are so very high and rugged on the moon, as we shall presently see.

Atmosphere of the Moon. The moon has little or no atmosphere. This is proved by the fact that its surface always stands out with remarkable distinctness, there never being the slightest evidence of clouds or obscuring vapor. It is also shown by the fact that when the moon passes between us and the sun there is no luminous ring around it as there would be if it had an atmosphere. The difference is conspicuous when the planet Venus passes between us and the sun. This planet has an atmosphere and the illuminated ring of its gaseous envelope is visible when it is in a line with the sun.

One might well ask why the moon has no atmosphere. The theory has been suggested that it has been gradually absorbed by the rocks of the surface. This is not very probable because while the rocks may absorb some atmosphere, on the other hand, they also give it forth. As they disintegrate they liberate as a rule large quantities of gas. Also there are irregularities on the surface of the moon which, if interpreted as indicating volcanic activity in past times, means that large volumes of gases have been given forth from its interior.

A better explanation, and one which is almost certainly correct, is that the moon has not sufficient gravitative power to hold an atmosphere. As was explained above in connection with the atmosphere of the earth and the kinetic theory of gases, there is a tendency of the molecules of an atmosphere to escape from the bodies which they surround by darting off into space. The gravitative power of the moon is so slight that the opportunities for escape are much greater than in the case of the earth. Consequently, it is not unreasonable to suppose that the atmosphere of the moon, if it ever had one, has been lost into space, molecule by molecule. Of course, there is no guarantee that at any time in its history it ever had an atmosphere comparable to that of the earth. But in view of the activities that its surface shows were once taking place there, it seems probable that it would now have a greater atmosphere than observation shows exists, if it had not been lost in this manner.

Light and Heat Received by the Earth from the Moon. Direct observations of the amount of light and heat received from the moon show that at full moon we get about $\frac{1}{600,000}$ as much light and heat from the moon as from the sun. The average amount of light and heat received from the moon compared to that received from the sun is very much less than this, probably not more than one-fourth as great. Therefore, it follows that we receive more light and heat from the sun in 15 seconds than we do from the moon in a whole year. The passing of a cloud between the earth's surface and the sun for a few minutes reduces the amount of light and heat received more than it would be reduced if the moon were taken from our sky for a year.

It follows from these figures that the moon does not have a sensible effect in raising the temperature of the earth. It is seen from this how absurd it is to suppose that hot spells or cold spells depend in any way upon the moon. As a matter of fact, the discussion of observations covering a very long time do not show any certain relation of any kind between the state of the weather and the phases of the moon. So far as can be determined from observations extending over a century there is no more likelihood of its freezing or raining or being hot at one phase of the moon than at another.

Temperature of the Moon. The average distance of the moon from the sun is about as great as that of the earth, and consequently if its atmosphere were the same and its rotation were the same its climate would be similar to that of the earth. The most important difference in this connection between the earth and moon is that the moon has no atmosphere. Therefore, the day side of the moon is subject to the intense rays of the sun with no protection of clouds or atmosphere, and the night side loses its heat rapidly and the temperature falls very low.

It was explained above that the moon keeps the same face toward the earth all the time, and consequently that it turns on its axis once in a month. Its day is, therefore, a synodic month of 28.5 of our days. This long period of rotation adds to the extremes of temperature which the moon already is shown to have because of the absence of an atmosphere surrounding it. For more than 14 of our days its surface is subject to the burning rays of the sun, and then for more than 14 of our days it is in darkness. During the long period it receives light and heat from the sun its temperature rises very high, probably reaching the boiling point. During the long night its temperature falls very low, perhaps 200° or 250° below zero. The lowest natural temperature ever known upon the earth, even in arctic regions, is about 90 degrees below zero.

The temperature of the moon can not be found without some difficulty. We have instruments which can measure as small amounts of heat as the moon sends to us but the difficulty arises in this case from the fact that the heat we receive from the moon is partly radiated heat and more largely reflected sunlight and heat. It is not possible to fully separate the two. If it were, and we had the amount of heat the moon radiates to us, we should be able to obtain its temperature with a considerable degree of accuracy. The best time for doing it and the one in which the reflected light and heat do not seriously bother is when the moon passes into the earth's shadow. Just before it enters the shadow it has been subject to the rays of the sun falling almost perpendicularly upon it. It enters the shadow and the sun's light and heat are cut off. (See Fig. 56.) The only heat which the observer at *O* receives from the moon at this time is that which the moon radiates because its temperature has been raised before it entered the shadow of the earth. This heat has been measured and from it we have arrived at our ideas concerning

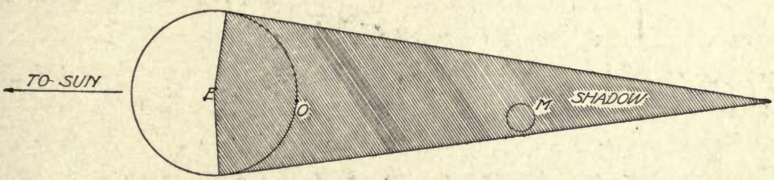


Fig. 56. The Earth's Shadow and Eclipse of the Moon

the temperature of the moon. It is an interesting and significant fact that, during the two hours required for the moon to pass through the earth's shadow, its temperature falls so low that at the end of the eclipse we do not receive sensible quantities of heat from it.

The moon is, therefore, to be thought of as a body whose surface is subject to alternating periods of burning and freezing temperatures. Clearly, it is impossible for life such as we have upon the earth to exist on such a body. There is every reason to believe that it is a dead world and probably that it has always been without life of any form.

Surface Conditions on the Moon. The moon appears to be an object of light and dark areas as viewed without a telescope. Through a telescope the same regions are still apparent, but it is found that those which are light are extremely rough while those which are dark are relatively smooth. Fig. 57 shows a photograph of the full moon in which to some extent the light areas and the dark areas can be made out, and can be seen to be, respectively, rough and smooth.

The most striking feature on the moon is a great number of circular pits varying in diameter from a few thousand feet up to more than 100 miles. These depressions are called *craters*. It must not be inferred, however, from the name that they are necessarily similar, either in their general features or in their origin, to the

Fig. 57. The Full Moon Photographed at the Yerkes Observatory

volcanic craters we have upon the earth. They are usually deep depressions in the surface of the moon with no evidence of lava flows around them, and often, if not generally, with high mountains in their interiors. In many cases if their rims were piled into the depressions they would not be filled.

The question of the origin of the lunar craters is not easy to answer with any degree of certainty. Arguing from analogy with the earth one might suppose they are of volcanic origin. However, the peculiarities noted above are against this theory. It seems less improbable to suppose that they have been formed by explosions of vast accumulations of gas in the interior of the moon. If we suppose its temperature was high near the surface, and that in contracting large quantities of gas gathered here and there at shallow depths, it is not altogether unreasonable to suppose that because of the high temperature the gas would occasionally tear its way out through the surface with explosive violence. In such an explosion matter would be thrown far and wide, depending upon its violence, and much of it would fall back into the cavity from which the gas escaped. It is not entirely unreasonable to suppose the craters may have originated somewhat in this fashion. If they have, the violence of the explosion is attested by the long cracks in the rocks radiating from the biggest craters and in some cases reaching to a distance of more than a thousand miles. They are conspicuously shown around several craters in Fig. 57.

Another hypothesis as to the origin of craters, which has perhaps some merit, is that they were formed by the impact of huge meteorites striking on the moon from without. In order to form in this manner those large craters which are approximately 100 miles in diameter, it would be necessary that meteorites very many miles in diameter should strike the moon. According to this theory the craters should be depressions, as they are seen to be, and there is no reason why the matter which constitutes their rims should fill them if it were put on the inside. One serious objection to this hypothesis is that the craters are all very nearly circular. If they were formed by the impacts of meteorites it would be expected that some of them would strike the moon glancing blows and make long streaks instead of circular pits. If the impact theory is the true explanation of the origin of the lunar craters, the heat generated by the impact of the meteorites is not a negligible quantity in accounting for their peculiarities. A meteorite striking the surface of the moon with the velocity at which meteors enter the earth's atmosphere, would generate enough heat to liquefy and volatilize a considerable fraction of the matter in the neighborhood of the point where it struck. This sudden heating of the matter in the interior of the crater pits would cause secondary explosions and might perhaps elevate the mountains which are found in them.

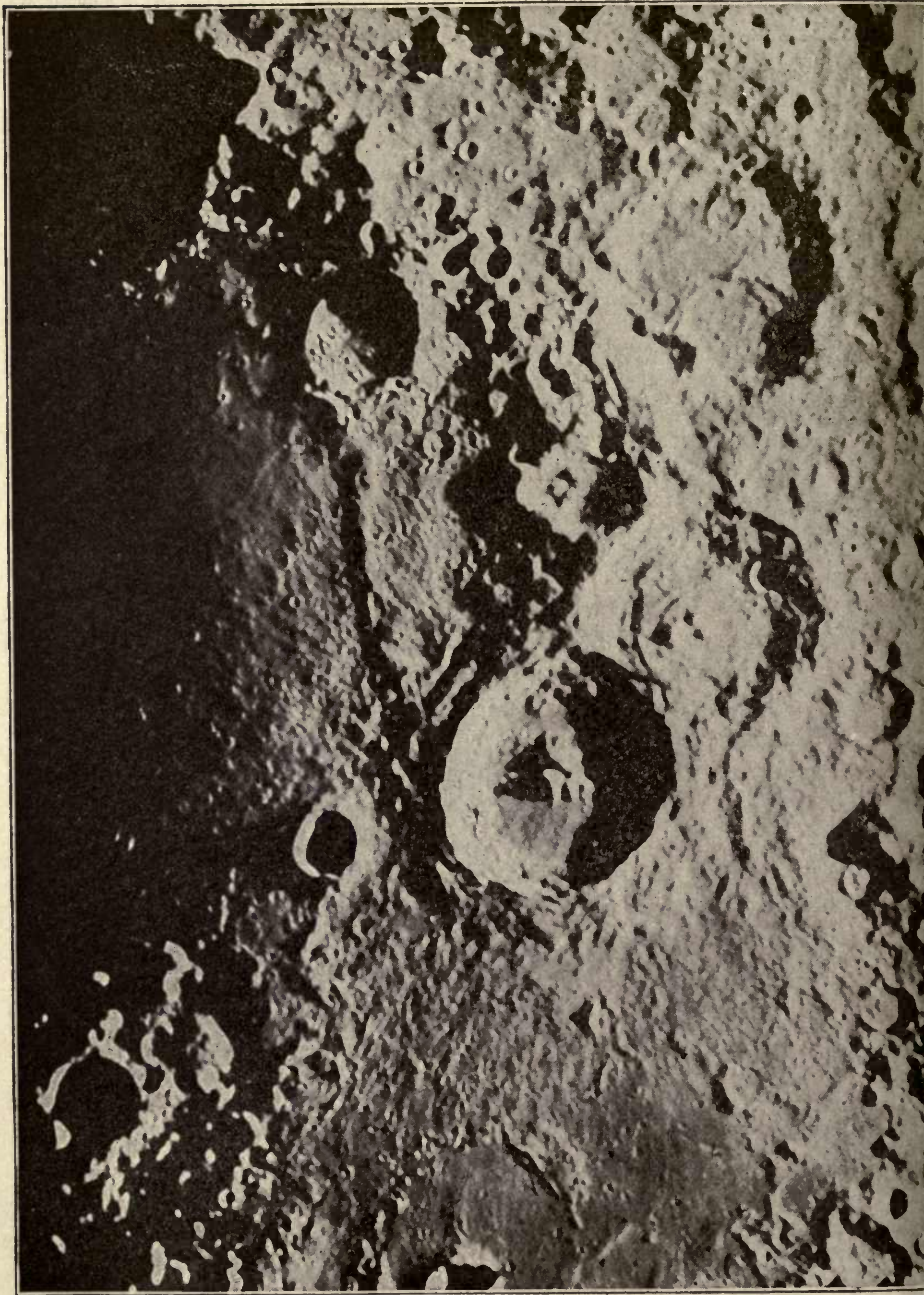


Fig. 58. The Crater Theophilus 64 Miles Across and 18,000 Feet Deep

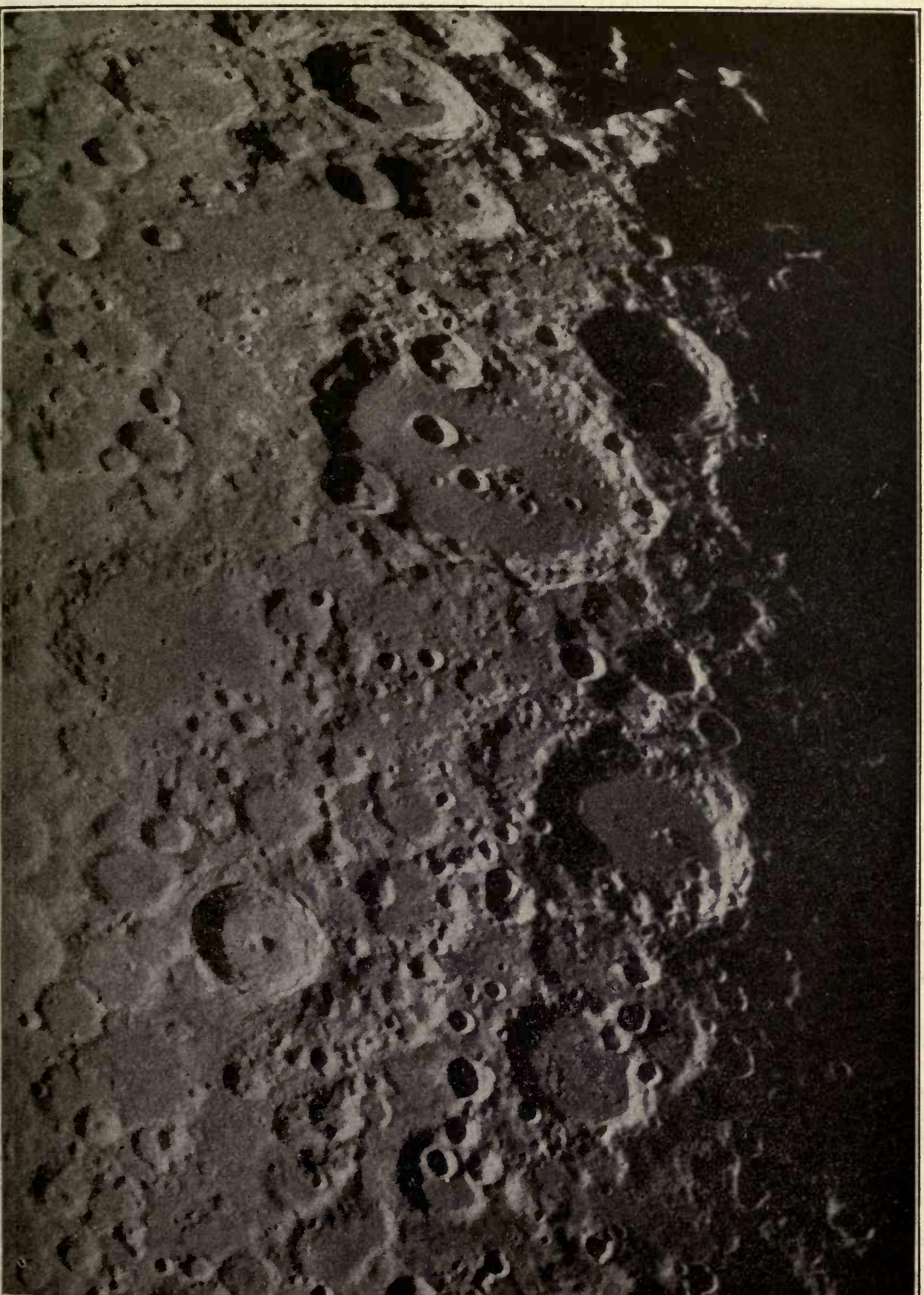


Fig. 59. The Great Crater Clavius and Surrounding Region

If the craters of the moon had their origin in the impacts of the meteorites from the outside the question arises why the earth has not been subject to a similar bombardment. These two bodies have been associated throughout their evolution as distinct bodies and there is no reason assignable why the moon should have been more subject to the impact of meteorites than the earth. The reason

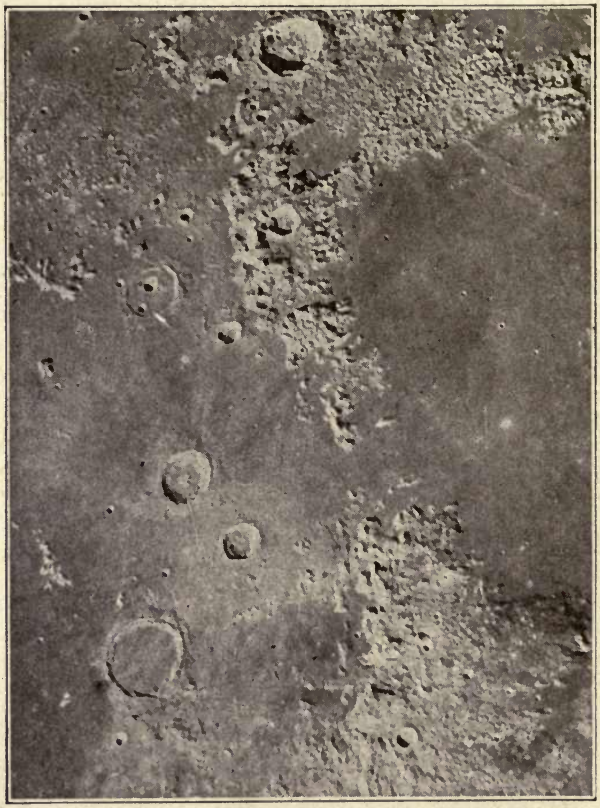


Fig. 60. The Lunar Apennines, Named by Galileo Who First Saw Them

for the absence of such evidence on the earth is that the earth has an atmosphere surrounding it and is nearly covered with water. These elements disintegrate the rocks, and in the course of the millions of years which have elapsed since such a bombardment has taken place, if indeed it ever did take place, the evidences of these impacts have been totally destroyed. On the other hand, on the moon there is no atmosphere and no water and the rocks would be preserved as they were originally formed. The chief disintegrating effects are the extremes of temperature which have been described above.

One of the most interesting craters is Theophilus, a photograph of which is shown in Fig. 58. This crater is 64 miles across. Its depth is from 16,000 to 19,000 feet. This result is obtained by measurements of the length of the shadows in its interior, knowing the altitude of the sun as seen from the moon when the photograph was taken. It is simply the problem of determining the height of a building from the length of its shadow when the altitude of the sun is known. In the interior of Theophilus there are mountains which are about 16,000 feet high. In the photograph their shadows can be seen stretching off to the left, long, sharp, and spire-like. They show the rugged character of these mountains. They stand up from the floor of the crater higher than any mountains on the earth reach above the plateaus on which they rest.

There are many places on the moon where a number of generations of craters can be seen. In Fig. 59 it is possible to see large old craters and new ones formed on their remains and in their interiors.

The moon has a number of mountain ranges and very many isolated peaks. One of the most remarkable ranges is the Apennines, Fig. 60, named by Galileo after the Apennines of Italy. These mountains are extremely rugged and very high, many of their peaks towering more than 20,000 feet above the plateaus on which they stand.

Fig. 61 shows a photograph of one of the dark, relatively smooth places called by Galileo *Mare Serenitatis,* or the Serene Sea. With his little telescope he was not able to discern the craters which we see in it and the ranges of hills which are running across it. Since we have mountains on the earth and also on the moon, he came to the conclusion that these two objects were very similar. Therefore, it was natural for him to suppose that there were seas on the moon as well as on the earth, and these smooth places were the only things which could be interpreted as being vast bodies of water. It is now clear that there is no water there whatever, and there is no evidence that there ever has been any. In all probability the side of the moon which we never see is in all essential respects similar to that which is toward the earth.

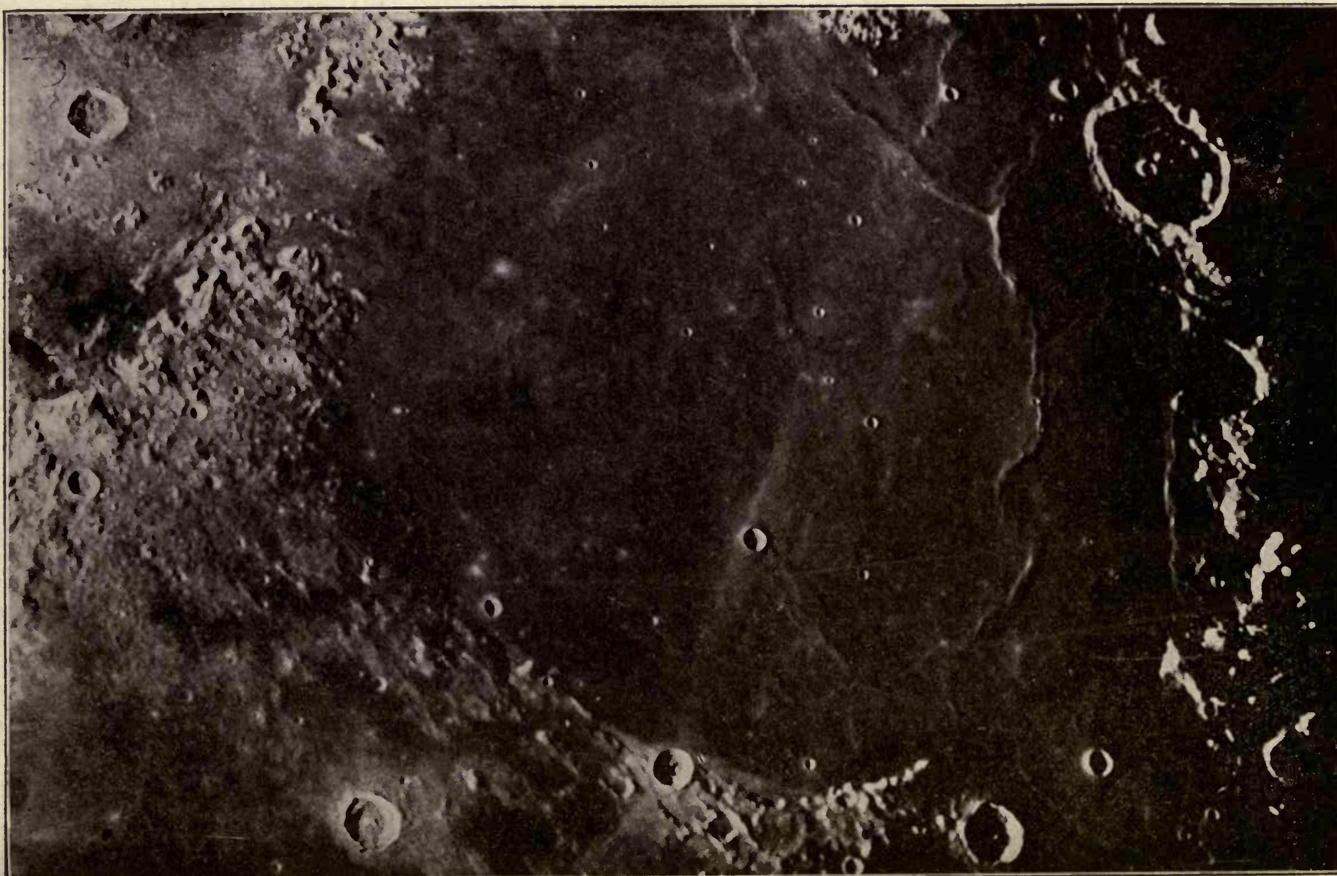


Fig. 61. Enlarged View of *Mare Serenitatis*

Besides the craters, the mountains, and the plains of the moon, there are a number of remarkable long, narrow, and deep cracks in its surface called rills. In some respects they resemble the Grand Cañon of the Colorado more than anything else on the earth. But the Grand Cañon of the Colorado was made by the river cutting its way through the rock; while the rills on the moon have certainly had a different origin. They may be simply cracks in the rock of the shrinking mass. If the cracks were made on the moon by the breaking rocks it was certainly shaken by severe earthquakes, for it is well known that earthquakes here on the earth are usually, if not always, produced by the breaking of the rocks of the earth's crust and their slipping on each other. For example, the destructive earthquake in San Francisco in 1906 was due to a crack nearly parallel to the coast several hundred miles in length, and the slipping of the rock on one side of the crack past that on the other side.

Eclipses of the Moon. When the moon passes into the earth's shadow it is eclipsed. It might be imagined from Fig. 48 that the

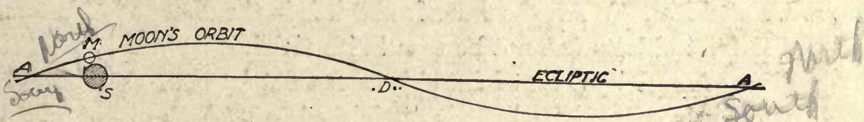


Fig. 62. The Moon Is Not Eclipsed Every Month Because Its Orbit Is Inclined to the Eclipti

moon would be eclipsed every time it is full. The reason it is not is because the plane of its orbit is inclined to the ecliptic about five degrees. Since the sun apparently travels on the ecliptic the shadow of the earth travels along the ecliptic. In Fig. 62 let the straight line represent the ecliptic and the curve the moon's orbit. Let the circle S represent the cross section of the shadow of the earth at the distance of the moon. Let M represent the moon. The point A is the place where the moon's orbit crosses the ecliptic from south to north, and is called the *ascending node,* while D, the other place where the moon's orbit crosses the ecliptic, is called the *descending node.* If the moon passes the earth's shadow when it is near A and D, clearly it will pass through the shadow and be eclipsed. If it passes the shadow when it is between A and D and not when near one of these points, it will miss the earth's shadow and will not be eclipsed.

The moon travels around the earth about 13 times in a year and consequently passes the earth's shadow about 13 times in a year. At two of these times it passes the shadow near the points *A* and *D*, and at these times the moon is eclipsed. The other eleven times the shadow of the earth is so far from *A* and *D* that the moon does not pass through it. It is easy to see, therefore, why the moon is not eclipsed every month, and why it is eclipsed twice a year on dates which are six months apart.

The points *A* and *D* are not fixed on the ecliptic. The attraction of the sun for the moon disturbs its orbit and causes the points *A* and *D* to move backward along the ecliptic. For this reason the eclipse at *A* occurs earlier each succeeding year; and similarly at *D*. The points *A* and *D* make a revolution in about 19 years. Consequently, the time of eclipses shifts throughout the whole year in a period of 19 years.

The chief scientific uses of an eclipse of the moon are to determine its temperature, as described above, and to search for its possible satellites. When the moon is new it is in the direction of the sun and faint objects can not be seen in its vicinity. When it is full it gives so much light that faint objects can not be seen near it. But when it is eclipsed its light is diminished to such an extent that if there were any small satellites revolving about it we should have a good chance of photographing them. Up to the present time no satellites of the moon have been discovered and there is no particular reason for believing they exist.

Eclipses of the Sun. If the orbit of the moon were exactly in the plane of the ecliptic, the sun would be eclipsed at every new moon. But the inclination of the moon's orbit causes this phenomenon to be relatively rare. In Fig. 62 we may think of *S* as representing the sun itself instead of the earth's shadow. The moon passes the sun 13 times a year, but passes between the earth and the sun only when the passage is made near *A* or *D*. Therefore, the eclipses of the sun occur only twice in the year, six months apart. This statement requires a slight correction because, if the sun is eclipsed when it is to the left of *A*, it is possible under certain circumstances for the moon to make a revolution of the sky and partially to eclipse it again when it is to the right of *A* and still near to it. The circumstances are similar relative to the point *D*. It is possible, therefore, to have four eclipses of the sun in a year. Hence, taking the lunar and solar eclipses together it is possible to have six in a year, two of the moon and four of the sun.

Relative Number of Eclipses of Sun and Moon as Observed from Any One Place. In Fig. 63, suppose S represents the sun, E the earth, and M_1 the moon at the time it is eclipsed. This eclipse can be seen from the half of the earth on the side toward it. Since it takes the moon about two hours to pass through the earth's shadow, the eclipse is visible not only to half the earth, but also to the part which is rotated into view of it during the two hours. Since there are two eclipses of the moon a year and each one is visible to at least half the earth, it follows that on the average at every place on the earth one eclipse of the moon per year is visible.

Let M_2 represent the position of the moon when the sun is eclipsed. The sun will be eclipsed only within the part of the shadow

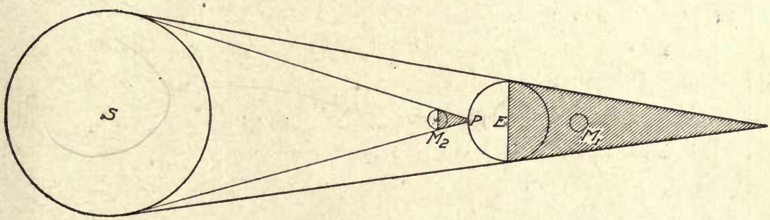


Fig. 63. Diagram for Explaining the Reason of Eclipses of the Moon and Sun

cone from the moon which strikes the earth, *i. e.*, at the region P. The moon, passing around the earth, causes this shadow to strike across the earth in a path whose width is generally less than 100 miles, and whose length is a few thousand miles.

Fig. 64 shows the path of a total eclipse of the sun as given in the nautical almanac. It is seen from this how small a portion of the surface of the earth is totally shadowed during an eclipse. It follows that in spite of the fact that there are more eclipses of the sun than of the moon, the number observed at any one place is very much less. Everyone who has paid any attention to celestial phenomena has seen an eclipse of the moon, but comparatively few people have seen a total eclipse of the sun. While the path of totality is very narrow, there is a large region from which the sun is seen as partially eclipsed. A partial eclipse is relatively of small interest as compared with a total eclipse.

Fig. 65 shows the paths of total eclipses of the sun from 1894 to 1973. It is seen from this map that there are large regions of the earth from which a total eclipse is not visible, and in fact that only a small part of the whole earth is eclipsed at all, during the 80 years which it covers. The fact that total eclipses of the sun are startling and not very frequent led the ancients carefully to record them. Their records have thus been of assistance to historians in some cases in fixing the dates in ancient chronology. If an

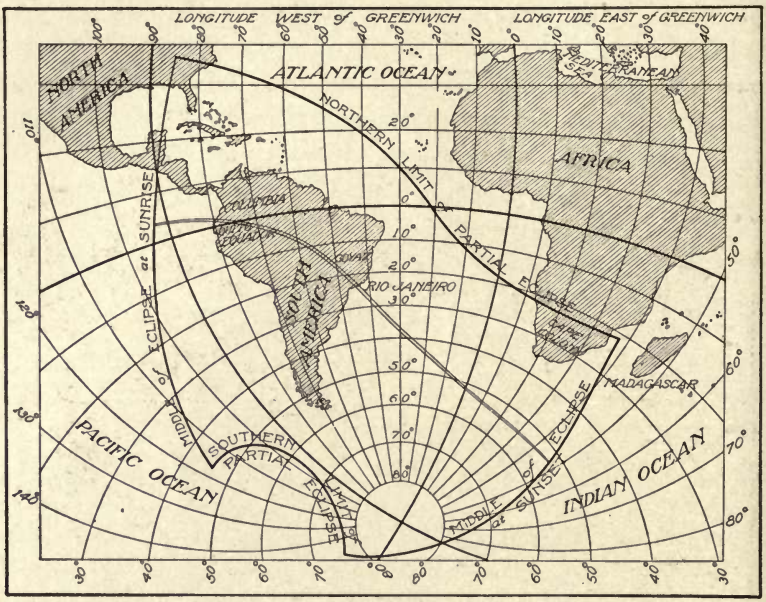


Fig. 64. Path of a Total Eclipse of the Sun

ancient chronicler described an eclipse at a certain place and stated the date of it in his system of counting time, it is possible to locate that date in our system of counting time, because the astronomers computing back across the centuries can tell the historians at what time an eclipse in that part of the world could have occurred.

One of the uses of the eclipses of the sun is the determination of the period of the moon around the earth. It is clear that at the time of an eclipse the moon is exactly between the earth and the sun. At some later time it is again between the earth and the sun and there is another eclipse. If the whole interval and the number of revolutions the moon has made in the meantime are known, it is possible to find the period of one revolution by dividing the whole time by the number of revolutions. The advantage in this method lies in the fact that eclipses have been observed for a very long time and the errors of observations are divided up because of the very many revolutions the moon has made in the meantime.

A second use of eclipses of the sun is the study of the atmosphere and corona of the sun. The corona is visible only at the time of total eclipses and is therefore subject to study only during the few minutes of eclipses which occur at rare intervals.

A third use of solar eclipses is that during the periods of totality

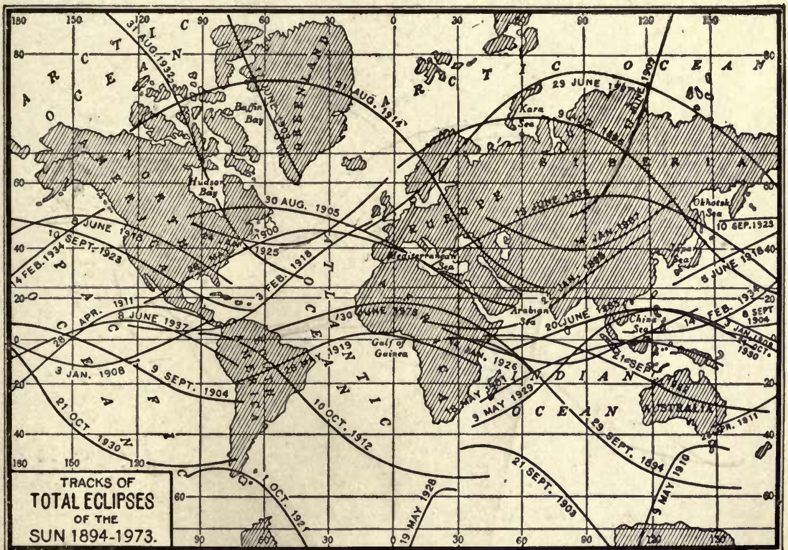


Fig. 65. Paths of Total Eclipses of the Sun

a search can be made for possible planets revolving so close to the sun that they are not visible unless its bright rays are screened off. A screen in the atmosphere covering it is of no use, for the illuminated atmosphere around is brighter than such objects would be. But the distant moon is beyond our atmosphere and when it eclipses the sun it makes the sky dark, allowing the region near the sun to be searched, particularly by photography, for undiscovered planets. So far none have been discovered, and now so many photographs have been secured during eclipses that it is improbable that any with a diameter exceeding 100 miles exists in close vicinity of the sun.

THE MOON'S DISK
The view shows the disk at 9¾ days, photographed with 40-inch refractor

ASTRONOMY

PART III

THE SOLAR SYSTEM

Members of the Solar System. The members of the solar system are the sun, the planets, and their satellites, the planetoids, the comets, and the meteors, though it may be that many of the comets and meteors are only temporary members of the solar family. The sun is in all respects the most important body in the system. Its gravitative power holds the planets in their orbits, and its light and heat illuminate and warm them. It is impossible to consider the planets and comets without considering their relations to the sun, but it is quite possible to discuss the sun without particular reference to the planets. For the present we shall be interested in all those members of the system except the sun.

There are eight planets in the solar system, which in the order of their distances from the sun are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. The first six have been known from prehistoric times. Uranus was discovered by Sir William Herschel in 1781, and Neptune was discovered by Galle in 1846.

The planetoids are like the planets, whence their name, except that they are very small and very numerous. Nearly all of them revolve around the sun in the region between the orbit of Mars and the orbit of Jupiter. The comets and meteors are wandering members of the system which pass around the sun in elongated orbits, sometimes going out so far they probably never return.

It is possible to find the distances of the planets in terms of the earth's distance by rather simple observations. In Fig. 66, let S represent the sun, E the earth, and V Venus. Suppose Venus is at its greatest apparent distance from the sun as seen from the earth. Then the angle at V is a right angle. The angle a is given by the observations. The angle at S is therefore known, since the sum of the interior angles of a triangle equals two right angles. Consequently, in the triangle ESV the angle at E and the angle at S are known and the included side ES is the distance from the earth to the sun. From this the distance SV can be computed. The problem is a little more difficult for planets which are farther from the sun than the earth is, but it is solved in essentially the same way.

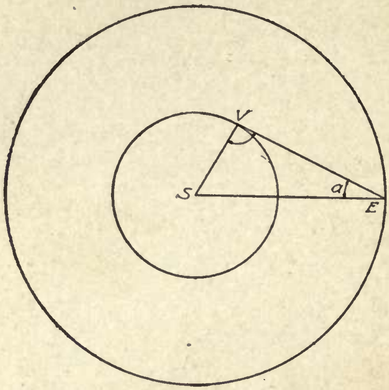


Fig. 66. Finding the Relative Distance of Venus from Observations at the Time of Its Greatest Elongation

Orbits of the Planets. The character of the orbits of the planets was first found by Kepler about 1618 by discussing particularly Tycho Brahe's observations of Mars. The three laws of planetary motion which he discovered are:

Law I. *Every planet moves so that the radius from the sun to it sweeps over equal areas in equal intervals of time, whatever their length.*

Law II. *The orbit of every planet is an ellipse with the sun at one of its foci.*

Law III. *The squares of the periods of any two planets are to each other as the cubes of their respective mean distances from the sun.*

To these laws, which relate to the fundamental properties of the motions of the planets, it might be added that the planes of the orbits of the planets are nearly coincident and that the planets all revolve around the sun in the same direction. It is also an important fact that the eccentricities of their orbits are in all cases small.

From Kepler's laws of motion Newton deduced most important consequences. He proved, in 1686, that it follows from the first law of motion that the forces to which the planets are subject are directed toward the sun. Before this time there was no well-established connection between the sun and the motions of the planets. In fact, it was generally supposed that there was some force continually urging the planets on in their orbits. As a preliminary to this conclusion Newton laid down the fundamental laws of motion given above in connection with the motions of the earth.

Newton also showed that it follows from Law II that the forces to which the planets are subject vary inversely as the squares of their distances from the sun. He proved in this connection that if this is the law of force the elliptical orbits are not the only ones possible. It is equally possible for a body to move subject to the law of gravitation in a parabola or a hyperbola. These curves are similar in many respects to the ellipse.

In Fig. 67 let *S* represent the sun and *E* an ellipse with one of its foci at *S*. If the point *A* on the ellipse is kept fixed and the one focus remains at *S*, and if the other end of the ellipse is moved away to the right to infinity, then the ellipse becomes the curve *P*, which is a parabola. A parabola has but one focus. The two arms of the parabola are more nearly parallel as the distance to the right increases, and approach exact parallelism as the distance to the right approaches infinity. If the arms of the parabola are opened out so that they are no longer ultimately parallel, we get the hyperbola *H*.

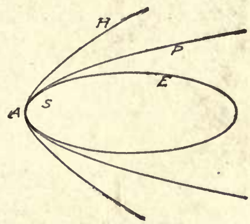


Fig. 67. Forms of Planetary Orbits

Some of the comets move in parabolas and possibly a few in hyperbolic orbits. It follows that they also move around the sun in obedience to the law of gravitation.

It follows from Kepler's third law that if all the planets were at the same distance from the sun they would be attracted by it the same per unit mass. This result is by no means self-evident. For example, the sun might attract different kinds of matter differently; and if so it would attract the planets differently if they were all at the same distance unless they were made of precisely the same materials in the same proportions. Since it is improbable that their different substances are in exactly the same proportion, it is improbable that, if gravitation were selective, they would all be attracted by the same amount if they were at the same distance.

Law of Gravitation. The law of gravitation is one of the greatest and most far-reaching discoveries ever made in science. Stated in its generality it is this:

Every particle of matter in the universe attracts every other particle with a force which is proportional to the product of their masses and which varies inversely as the squares of their distances apart.

It relates every particle in the universe to every other particle. If the position of any mass in the whole universe changes, the force which it exerts on every other particle in the universe is changed because, according to the law, force depends upon the distance. If a person moves, the gravitative force reaching out from him to the two farthest bodies is changed. If, as is now believed, every mental activity is accompanied by a physical change in the brain, then every thought is accompanied by a change of gravitative force throughout the universe. Of course, these changes are exceedingly minute and may be for all practical purposes entirely neglected. The point of interest here is the fact of their existence.

More immediate and important consequences of the law of gravitation are the motions of the heavenly bodies and their influences upon one another. After the law was once discovered it became an instrument for further discoveries. Time after time mathematicians have predicted, on the basis of the law of gravitation, things which ought to be observed and have told the observers when and where to look for them. The exactness of the law of gravitation is shown by the fact that their predictions have always been verified. No other law in all the realm of science is subject to such delicate tests and is proved with so high a degree of certainty. It is for this reason that it is used with such confidence in arriving at results which can never be reached by direct processes. For example, in the study of the interior of the earth it was inferred from the nature of the changes produced in the rotation of the earth by the attraction of the moon and sun on its equatorial bulge, that its interior is on an average very rigid. This result is no more certain than the laws and the observations upon which it is based. The observations are subject in this case to no serious error, and our confidence in the conclusion is great because of its being based upon the fundamental law of gravitation.

The law of gravitation was the most important discovery of Sir Isaac Newton, one of the greatest men the world has produced. In Westminster Abbey where England buries the members of its royal family and the great men it has produced, there is a tablet erected in honor of the memory of Newton on which is an inscription in Latin which translated reads: "Mortals, congratulate yourselves that so great a man has lived for the honor of the human race." This splendid tribute scarcely surpasses those expressions of esteem made by the foremost scholars of the world who have worked in the same line. The brilliant German, Leibnitz, who was a contemporary and in some respects a rival of Newton, said: "Taking mathematics from the beginning of the world to the time when Newton lived, what he had done was much the better half." The French mathematician, LaGrange, who was one of the greatest masters of celestial mechanics, said: "Newton was the greatest genius that ever existed, and the most fortunate, for we cannot find more than once a system of the world." The English scientist, Whewell, wrote in his "History of Inductive Science": "It (the law of gravitation) is indisputably and incomparably the greatest scientific discovery ever made whether we look at the advance which it involved, or the extent of the truth disclosed, or the fundamental and satisfactory nature of this truth."

Newton, with the humility characteristic of great minds who see how little they know compared with that which they do not know but would like to understand, said: "I do not know what I may appear to the world; but to myself I seem to have been only like a boy playing on the seashore and diverting myself in now and then finding a smoother pebble or a prettier shell than the ordinary, whilst the great ocean of truth lay undiscovered before me."

One of the satisfactory things in science is that in it are discovered fundamental laws such as the law of gravitation. It satisfies our instincts for absolute truth.

Distances of the Planets. The mean distances of the planets from the sun, which means half of the lengths of their orbits, are:

Mercury	36,000,000 miles
Venus	67,200,000 miles
Earth	92,900,000 miles
Mars	141,500,000 miles
Jupiter	483,300,000 miles
Saturn	886,000,000 miles
Uranus	1,781,900,000 miles
Neptune	2,791,600,000 miles

The diameter of the sun is about 866,000 miles.

The figures which have been given represent so vast distances, and cover so wide a range, that it is difficult to form any adequate mental picture from them. The relative dimensions of the system can be shown better by means of a diagram than by the numbers.

Suppose, for example, we should draw a map of the system, taking for the orbit of Mercury a circle one inch in diameter. On this scale the sun would be represented by a circle $\frac{1}{42}$ of an inch in diameter, and the earth by an invisible dot, scarcely more than $\frac{1}{5000}$ of an inch across. On the same scale the distance from the sun to Neptune would be a little over three feet. Consequently, it is not possible to put such a picture on the printed page. If we should represent the orbit of Neptune by a circle four inches in diameter, which is about as large as can be put on the page, the orbit of Mercury would be about $\frac{1}{20}$ of an inch in diameter. Obviously, then, it is impossible on the printed page to give a diagram showing the whole system to scale. However, this should not deter the reader from making such a diagram on a suitable place as, for example, on a blackboard or a very large sheet of paper.

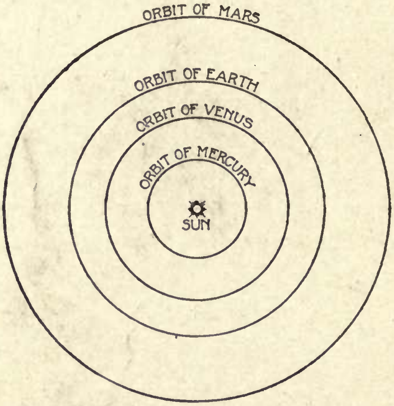


Fig. 68. The Orbits of the Terrestrial Planets to the Same Scale

Certain features of the system can, however, be brought out by means of the diagrams. Fig. 68 shows the orbits of the four planets nearest the sun to relative scale. It is apparent from the figure that they are spaced with a considerable degree of regularity.

Fig. 69 shows the orbits of the planets beginning with Mars and ending with Neptune. Now it is possible to imagine the orbits of the three planets which are nearer the sun than Mars inside the small circle which represents its orbit. From this diagram it is evident that the farthest planets are spread out at enormous distances. The space between the orbits of Jupiter and Saturn is much greater than all that interior to the orbit of Jupiter; and that between the orbits of Saturn and Uranus is greater than all of that interior to the orbit of Saturn; and similarly for the orbits of Uranus and Neptune.

The apparent diameters of the sun, as seen from the different planets, are inversely as their distances from the sun. The sun as seen from the earth has an apparent diameter of a little over half a degree. As seen from Mercury its apparent diameter is nearly three times this. Its apparent area, which varies as the square of its apparent diameter, is consequently nearly nine times as great as seen from Mercury as it is as seen from the earth. Considering the other extreme we find, since Neptune is 30 times as far from the sun as the earth is, that the apparent diameter of the sun as seen from Neptune is only one minute of arc. Now, a body whose apparent

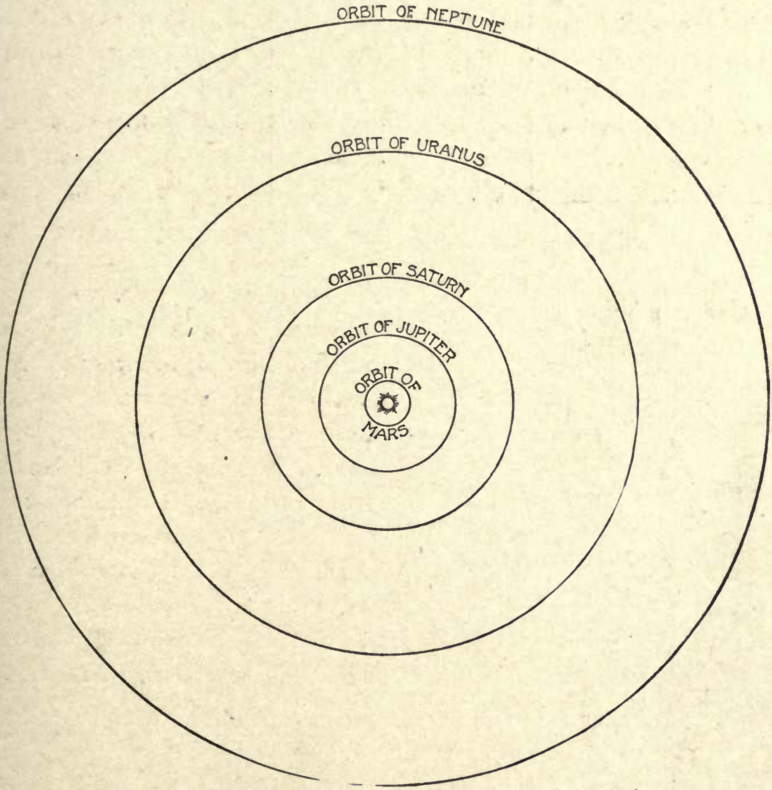


Fig. 69. The Orbits of the Major Planets to the Same Scale

diameter is less than one minute appears to the unaided eye like a point of light. Therefore, as seen from Neptune, the sun would appear like a star, only immensely brighter than any star in our sky. Its apparent area as seen from Neptune would be $\frac{1}{900}$ that as seen from the earth. Consequently, the amount of light and heat received on Neptune per unit area is $\frac{1}{900}$ that received by the earth. One is apt to draw the erroneous conclusion that Neptune is a rather dark place. But when we reflect that moonlight is equal to only $\frac{1}{600,000}$

TABLE IV
Planets in Order from Sun with Apparent and Actual Diameters

Planet	Greatest Apparent Diameter (seconds of arc)	Diameter (miles)
Mercury	13.	2,765
Venus	67.	7,826
Earth	...	7,913
Mars	25.	4,352 (equatorial) 4,312 (polar)
Jupiter	50.	90,190 (equatorial) 84,570 (polar)
Saturn	20.	76,470 (equatorial) 69,780 (polar)
Uranus	49.	34,900
Neptune	21.	32,900

of sunlight, while the illumination of Neptune is only $\frac{1}{900}$ that of the earth, it is seen that sunlight on Neptune is really an intense illumination, being about 700 times full moonlight here on the earth.

The climate of a planet depends to a large extent upon the amount of light and heat it receives from the sun. Other things being equal, particularly the constitution of the atmosphere and the radiation, the climate of Mercury would be the hottest of all the planets, and that of Neptune the coldest. Since Neptune receives so small an amount of heat and light compared to the earth, it is clear that unless its atmosphere is peculiarly adapted to preserving a high temperature or unless the planet is still hot itself, its surface must be very frigid.

Dimensions and Masses of Planets. The diameters of the planets differ almost as much as their distances from the sun. In a general way those which are near the sun are small, and those which are far away are large. Their actual sizes are found from measurements of their apparent diameters after their distances are known. Table IV, based on measurements by Barnard at the Lick Observatory, gives the planets in their order from the sun, in the second column their greatest apparent diameters as seen from the earth, and in the third column their actual diameters in miles.

The circles of Fig. 70 show better than these numbers the relative dimensions of the planets. The striking thing is the smallness of the earth with respect to the great planets.

Since the surfaces of similar bodies are as the squares of their like dimensions and the volumes as the cubes of their like dimen-

TABLE V
Surface and Volume of Planets as Compared to Earth

Planet	Surface	Volume	Planet	Surface	Volume
Mercury	0.12	0.04	Jupiter	122.0	1,350.0
Venus	0.98	0.97	Saturn	85.6	790.0
Earth	1.00	1.00	Uranus	19.5	85.8
Mars	0.30	0.16	Neptune	17.3	71.9

sions, it follows that the differences in surfaces and volumes of the planets are much greater than the differences in their diameters.

Table V gives the comparison taking the surface and volume of the earth as a unit.

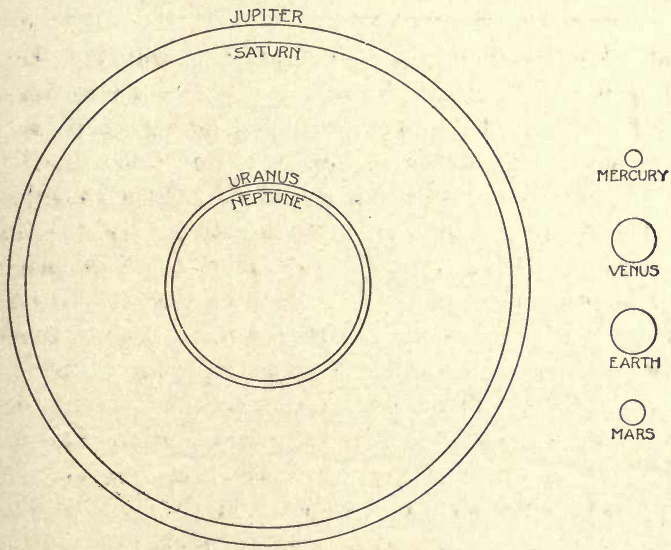


Fig. 70. The Planets Drawn to the Same Scale

The masses of the planets depend upon their size and upon their density. The masses of those that have satellites are found by the time it takes their satellites to revolve around them. It is easy to see that the greater the mass of planet the shorter will be the period of the satellite at a given distance. The formula relating their period, the distance, and the mass of the planet, is one which is derived from the law of gravitation and is given in celestial mechanics. It is

$$P = \frac{2\pi a^{\frac{3}{2}}}{k\sqrt{M+m}}$$

TABLE VI

Masses and Densities of Sun and Planets

Object	Mass (Earth = 1)	Mass (Sun = 1)	Density (Water = 1)
Sun	332,000.0	1	1.41
Mercury	0.033	$\frac{1}{9647000}$	3.70
Venus	0.82	$\frac{1}{405000}$	4.89
Earth	1.0	$\frac{1}{332000}$	5.53
Mars	0.11	$\frac{1}{3020000}$	3.95
Jupiter	317.7	$\frac{1}{1047}$	1.53
Saturn	94.8	$\frac{1}{3502}$	0.72
Uranus	14.6	$\frac{1}{22700}$	1.22
Neptune	17.0	$\frac{1}{19500}$	1.11

where P is the period expressed in days, a the distance from the satellite to the planet expressed in terms of the earth's distance from the sun, k a constant which equals about $\frac{1}{60}$, M the mass of the planet, and m the mass of the satellite.

The masses of those planets which do not have satellites are found from their attractions for one another, and for comets which pass near them. The planets are so far apart and they are so small compared to the sun that their mutual attractions are not large enough to enable us to determine their masses very accurately. When comets pass near them more exact results can be secured, but the best that can be obtained in this way is very much less accurate than those furnished by the periods of the satellites.

Since the diameters of most of the planets are known and their masses are found as has just been explained, it is possible to determine their densities by dividing the masses by the volumes. Table VI gives the results for the sun and the planets. In the second column the mass of the earth is taken as the unit, and the masses of the other members of the system are expressed in terms of it. In the third column the mass of the sun is taken as the unit; and in the fourth column the densities of all these bodies are given, taking water as the standard.

It is seen from Table VI that Jupiter is not only much larger than any other planet, but its mass is more than three times that of any other planet and about two and a half times that of all the other planets combined. It is also observed that the earth is the densest

TABLE VII

Comparative Surface Gravity of Sun and Planets

Object	Surface Gravity	Object	Surface Gravity
Sun	27.7	Jupiter	2.61
Mercury	0.38	Saturn	1.19
Venus	0.86	Uranus	0.88
Earth	1.00	Neptune	0.88
Mars	0.38		

member of the solar system. The rarest one is the planet Saturn, whose mean density is about three-fourths that of water.

The surface gravity, or the relative weight of an object on the surface of a planet, depends upon its mass and dimensions. According to the law of gravitation the weight, which is a consequence of the attraction, is directly proportional to the mass of the planet and inversely proportional to the square of the distance from its surface to its center. From this law and the preceding tables Table VII has been computed.

It is seen from Table VII that although the earth has a greater density than any other member of the system, its surface gravity is considerably less than that of Jupiter and the sun. In the case of Saturn its larger mass is almost exactly offset by its greater diameter.

Periods of the Planets. The periods of the planets depend upon their distances from the sun, the greater the distances the longer the period. In fact, the formula for determining the periods is given in the preceding article, where M in the present case must be taken to represent the mass of the sun and m the mass of the planet. The period referred to in the present connection is the time it takes a planet to revolve around the sun as observed from the sun. This is called the *sidereal period.* There is another period which is more important for observational purposes known as the *synodic period.*

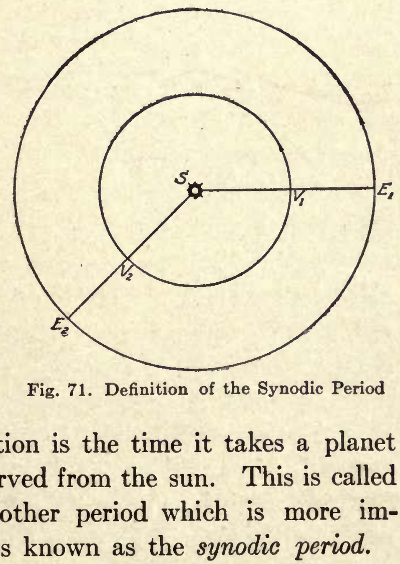


Fig. 71. Definition of the Synodic Period

In Fig. 71, let S represent the sun, and the two circles the orbits of Venus and the earth, respectively. Suppose at a certain time the sun, Venus, and the earth are in a straight line at SV_1E_1. Suppose the directions of motion are indicated by the arrows in the diagram. Venus moves faster than the earth both in miles per second and in angle; consequently, the line from S to V will move on ahead of the line from S to E, and after a time will gain a revolution on it. Let us suppose that by the time the earth gets around to E_2 Venus will have gone around its orbit back to V_1, and on the second time around up to V_2, so that it is again in a line with the earth. It will be seen by an examination of the diagram that, under the hypotheses, the

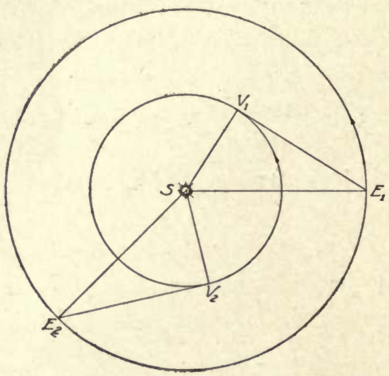


Fig. 72. Venus at Greatest Elongation

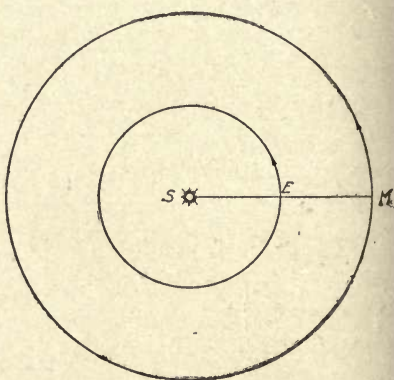


Fig. 73. The Planet Mars in Opposition

earth, Venus, and the sun have not been in a straight line since they were at SV_1E_1. This period from a certain relative position to the same relative position again is called the *synodic period*.

Instead of supposing that the earth, Venus, and the sun are initially in a straight line, we might start from the time Venus seems to be farthest from the sun, as indicated in Fig. 72, with the earth at E_1 and Venus at V_1. In this case when the earth gets to E_2, Venus will be at V_2 and will again be at its apparent greatest distance from the sun. This is also a synodic period and exactly equal to the preceding. When the earth, Venus, and the sun are located relatively to each other, as indicated in Fig. 72, Venus is in the position best observable from the earth. If the planet were farther from the sun than the earth is, the straight line situation, indicated in Fig. 71, would be the time when observations could be most advantageously made. When the relations are as indicated in Fig. 72, the planet is said to be in greatest elongation. That is, as it is observed from the earth it is farthest out from the sun. When the situation is as indicated in Fig. 71, the planet is said to be in *conjunction* with the sun. In Fig. 73, which shows the orbit of the earth and Mars, the planet is said to be in *opposition* when the relations of the bodies are as indicated in the diagram. In observing a planet which is farther from the sun than the earth, obviously the most convenient time for observations is when it is in opposition, for then it is nearest to the earth and the illuminated side is toward the earth

It is obvious from Fig. 72 that a planet which is nearer the sun than the earth, can have an elongation either side of the sun. If the planet is to be observed in the evening, which means that it must be above the horizon after the sun has set, it must be east of the sun. Since the evening is in general a more convenient time for observation than the early morning, we shall make our calculations for the eastward elongation. Since the earth rotates in the same direction that it goes around the sun, viz, from west to east, it follows that Venus has a westward elongation when its relations to the sun and the earth are as indicated in Fig. 72. This can be seen by following a point on the earth in its daily rotation. The point will pass under Venus, *i. e.*, Venus will apparently cross its meridian, before it passes under the sun, and consequently Venus will set before the sun does.

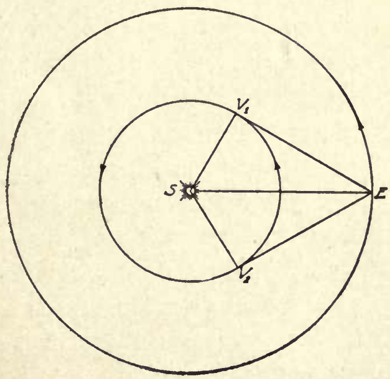


Fig. 74. The Motions of Venus Eastward and Westward Past the Sun

Suppose Venus has its greatest eastward elongation and consider Fig. 74. When Venus is in the position V_2, it has its greatest eastern elongation. Suppose for simplicity that the earth stands still while Venus moves forward in its orbit. It will pass between the earth and the sun and arrive at its greatest westward elongation at V_1. Then it passes apparently back across the sun on the side of the sun opposite to the earth and arrives again at V_2. It is clear from the diagram that the time from V_2 to V_1, *i. e.*, from eastward elongation to

TABLE VIII

Data from Which to Compute Times Favorable for Observation of Planets

Planet	Sidereal Period (Years)	Synodical Period (Years)	Date of Eastern Elongation or of Opposition
Mercury	0 24	0.32	July 24, 1912
Venus	0.62	1.63	July 6, 1911
Earth	1.00	——	——
Mars	1.88	2.136	Nov. 24, 1911
Jupiter	11.86	1.092	May 31, 1912
Saturn	29.46	1.035	Nov. 22, 1912
Uranus	84.02	1.012	July 24, 1912
Neptune	164.78	1.006	Jan. 13, 1912

westward elongation is longer than the time from V_1 to V_2. The same thing is true when the earth moves forward in its orbit. And similar statements are true for the planet Mercury whose orbit is also inferior to that of the earth. Since the orbit of Mercury is smaller, these differences just mentioned in the time of passage from one elongation to the other are less than in the case of Venus.

The planets which are nearer the sun than the earth are called *inferior planets,* and those which are farther from the sun, *superior planets.* Suppose an inferior planet is observed at its greatest eastern elongation. The question is when will it again be in that favorable position for observation. This is its *synodical period.* It can be determined by observations, or it can be computed without difficulty from the sidereal period. In the case of a superior planet the time for the most favorable observation is in opposition, and after the synodical period the planet will have returned to that relative position. Hence, it follows that in order to find the time when a planet will be favorably situated for observations it is necessary to know once when it was in eastern elongation if it be an inferior planet, or in opposition if it be a superior planet, and then to add enough synodical periods to arrive at least to the date of computation. For example, suppose it were known that Mars was in opposition in 1900 on a certain date and that its synodical period was exactly two years; and suppose in 1911 one wished to know when it would again be in opposition. If he added five of the two-year periods it would bring the date forward to 1910, which having already passed by would not give the observer the information he desired. But adding six periods he would find that in 1912 on a certain date Mars would again be in opposition, and he could be prepared to observe it. Of course, in actual practice the numbers do not come so simply as in the example.

Table VIII gives the sidereal and synodical periods of the planets, dates of great eastern elongations in the case of the inferior planets, and of opposition in the case of the superior planets. From these dates and the synodical periods the times favorable for observations of the planets can be determined for as long a period as is desired.

The Two Groups of Planets. It is evident from the preceding data, which give a general idea of the solar system considered as a whole, that the planets naturally fall into two groups which are distinct in many of their characteristics. The first group comprises Mercury, Venus, Earth, and Mars, and is called the *terrestrial group* from the general similarity of these bodies to the earth. Jupiter, Saturn, Uranus, and Neptune constitute the other group, called the *major planets* because of their relatively great size. The distinction in the two groups is seen from the fact that the major planets are on the average 17.6 times as far from the sun as the terrestrial planets. On the average the terrestrial planets receive per unit area 310 times as much heat and light from the sun as the major planets. On the average the diameter, surfaces, and volumes of the major planets are 10, 100, and 1,000 times greater than those of the terrestrial planets. The masses of the major planets average 224 times those of the terrestrial planets, while their densities are only a little over one-fifth as great. The periods of revolution of the major planets average 77.6 times those of the terrestrial group and, as we shall see, their periods of rotation so far as they are known average less than one-half of those of the terrestrial planets. These facts are sufficient to establish the grouping of the planets which has been adopted.

Notwithstanding the diversities among the members of the two groups of planets, there are many harmonies among all of them considered together. The harmonies are fully as important as the diversities. The foremost of the harmonies to be noted is that the planets and more than 700 known planetoids all revolve around the sun in the same direction and nearly in the same plane. The greatest divergencies from the plane of motion are in the case of the planetoids, The sun rotates in the same direction and, indeed, so do all the planets whose rotations are known. The moon revolves around the earth in the same direction and rotates in this direction. In fact, the satellites of all the planets except one each of Jupiter and Saturn, and the satellites of Uranus and Neptune, revolve in this same direction. All the orbits are very nearly circular. Often this does not strike one as being a fact of any significance, but when it is remembered that it is just as natural for the orbit of a body moving subject to the law of gravitation to have any eccentricity, it does, indeed, seem to be a remarkable fact. It is as remarkable as it would be if one were to find the trees in a natural forest all arranged in definite straight lines.

The Planetoids. If the distances of the planets from the sun are examined, it will be found that each one is approximately twice that of the preceding one with the exception of Jupiter, whose distance is about 3.5 times that of Mars. A more exact method of finding the relative distances is to take the numbers 0, 3, 6, 12, 24, 48, and so on, and to add to each of them 4. The sums thus obtained are very nearly proportional to the distances of the planets from the sun, with the exception that there is a number falling between the distance of Mars and Jupiter. This arrangement of numbers, known as "Bode's Law," though it was discovered by Titius, led astronomers at the end of the eighteenth century to suspect that another planet existed between the orbit of Mars and that of Jupiter. Bode's law is not a law in the same sense that the law of gravitation is, for it expresses the facts only roughly, and no actual connection between them and it has ever been established. However, it was enough to direct inquiry toward the existence of an unknown world. In 1800 a number of German astronomers founded an association whose purpose was to search for the unknown planet. The difficulty in a problem of this sort arises from the fact that a small planet does not look materially different from a star, and it is necessary to find in some way whether the object viewed is a star or not. One way of detecting it is to find whether the object moves relatively to the stars or not. If so, it is not a star. Consequently, one way to find whether there are any worlds undiscovered is to make a map of all the objects visible with the instruments in use, and then at a later date to see whether they have the same positions or not. While the discussion of the astronomers was going on, and while they were making preparations to carry out extensive observations in the search, the philosopher Hegel proved, or at least claimed to have proved, by the "most conclusive reasoning," that there were no unknown planets, and remarked on the folly of searching for them. Before the German astronomers actually got to work, and indeed shortly before the publication of Hegel's dissertation, an Italian astronomer, Piazzi, at Palermo, discovered an unknown world January 1, 1801, on the first day of the nineteenth century. He named it Ceres after the tutelary goddess of Italy.

In 1801, communication was slow compared to that which we have at the present time. The news of the discovery of Piazzi did not reach Germany until the following spring and by that time the sun had passed between the earth and the planet and the latter was lost to view. Up to that time it was not known how to compute an accurate orbit of a planet from a few observations. The problem of getting the orbit of Ceres and the rediscovery of it led a brilliant young German mathematician by the name of Gauss to develop a method for doing it. In accordance with his computations, which directed observers where to look in the sky to find this world, it was again picked up. It was found upon examination and measurement that its orbit was between that of Mars and Jupiter, at about the distance Bode's law would lead one to expect an unknown world to be found. The new planet was surprisingly small. According to recent measurements of Barnard its diameter is 485 miles.

In March, 1802, Olbers discovered a second planetoid which he named Pallas, and in September, 1804, Harding found a third which he called Juno. Olbers discovered again another in March, 1807, which is known as Vesta. After the second planetoid was discovered it was supposed that perhaps they were the fragments of some larger planet which for some unknown reason had exploded. If we imagine a planet going around the sun and exploding at some point in its orbit, after the explosion the fragments will go on their way around the sun in distinct elliptical orbits. But since all elliptical orbits are closed they will all return to the point where the explosion took place. The period of a planet depends upon the length of its orbit, and as the different fragments might move in orbits having different lengths they would not all return to the point of the explosion at the same time. If this theory were correct, the position in the sky to search for the fragments of an exploded planet would be that where they cross. After two planets had been discovered the computations showed the two points where their orbits intersected, and consequently if the explosion theory were correct, the other fragments should be discovered some time at one of these two places. Since this theory was at first adopted, though it has long been abandoned, the search was prosecuted most carefully in the vicinity of the points of intersection of the orbits of the planetoids.

After the discovery of the first four planetoids no other one was discovered until 1845. This world was picked up by Hencke after

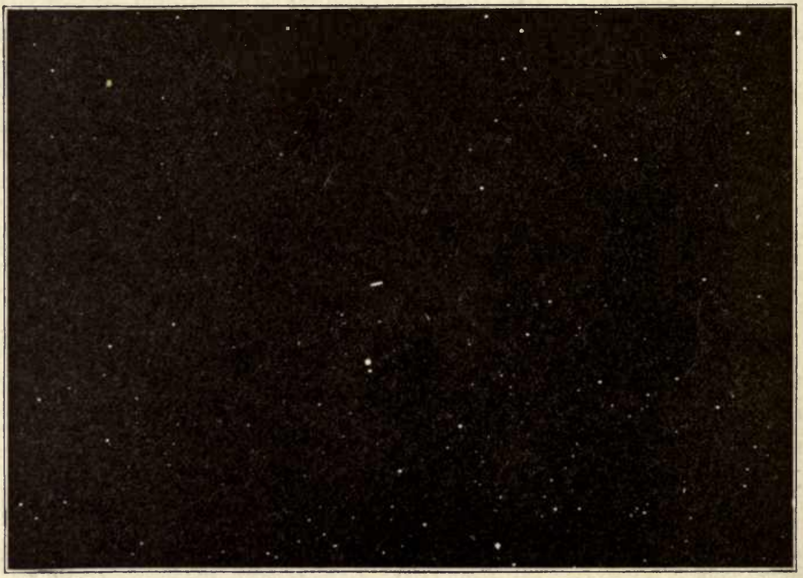


Fig. 75. A Planetoid Trail Photographed at the Yerkes Observatory

fifteen long years of search. Few men would have the patience to sit at the eye end of a telescope night after night and week after week for fifteen years before making a discovery. After 1847, catalogues of the stars were so extensive that it became a relatively easy matter to discover these objects, which were found to be very numerous. But a new epoch in their discovery began in 1891 when Wolf, at Heidelberg, discovered one by photography. The method is extremely simple. The photographic plate is given a long exposure in a certain region with the telescope following the stars so that their images come out on the plate as points. The planetoids move among the stars, and if there is one in the field of view its image will come out on the plate as a little streak. Fig. 75 shows one of these photographs with a planetoid trail at the center of the picture. These little trails show planetoids and lead very quickly and conveniently to their discovery. In some cases more than one has been found on a single plate. There are at the present time over 700 of them known.

The old theory that the planetoids had their origin in an exploded planet has been abandoned because the orbits extend all the way from that of Mars out to that of Jupiter, over a distance exceeding 300,000,000 miles. The planetoids nearest the sun are, at their nearest approach to those which are near Jupiter's orbit, more than three times as far from them as the earth is from the sun. In fact, one was discovered in 1898 whose orbit is between the orbit of the earth and that of Mars, and more recently others have been discovered whose distances from the sun are equal to that of Jupiter.

The first planetoids discovered were naturally the largest and brightest ones and their diameters were from 100 to 500 miles, probably the latter figure being the extreme limit. Those of recent discovery are much smaller, probably ranging down to approximately 10 miles in diameter. The probabilities are that there are unlimited numbers of them still smaller. It is impossible to determine their mass since they exert no appreciable gravitational influence on other known bodies, but if their densities are comparable to those of the planets, their combined mass is probably not $\frac{1}{100}$ that of the earth. If it were greater than this its attraction on Mars would sensibly disturb the orbit of this planet. Computations referring to these planetoids so far discovered, and based on what seem reasonable assumptions regarding their density, show that their mass is less than $\frac{1}{3000}$ that of the earth.

Being compelled by the observations to abandon the explosion theory of their origin, one might inquire how they have arisen. This problem is wrapped up with that of the origin of the planets. Apparently, the zone between the orbit of Mars and that of Jupiter was one in which there was considerable material, but in which no body of dominating gravitative influence existed to sweep up and gather to itself the widely scattered fragments. We shall take up again the question of the origin of the planets.

The planetoid whose orbit is between that of the earth and Mars, known as Eros, presented some remarkable peculiarities to astronomers. In February and March, 1901, about three years after its discovery, its light began to be variable. At its minimum it was less than one-third as bright as at its maximum, and the period from maximum to minimum was only 2 hours and 38 minutes; or, perhaps, 5 hours and 16 minutes, composed of two sub-periods of 2 hours and 25 minutes and 2 hours and 51 minutes, respectively. In a few months it again was shining with steady light. Since all these bodies shine entirely by reflected light, it is difficult to account for these variations. One suggestion for explaining them was that Eros is really composed of two bodies near together which revolve around their common center of gravity. If this were so, when the bodies were in a line with us they would present less surface than when they were sidewise, and consequently would appear fainter. But according to this theory it is impossible to account for so great variations in the light as the observations actually show existed.

Another hypothesis for the explanation of the variability of Eros is that the reflecting power on various parts of it differs greatly. According to this theory, when the highly reflective side is toward us it appears bright, and when the duller side, darker. If this were true, we should have the period of rotation from the observation of the changes in its light. The chief difficulty arises when we attempt to explain the large variability for a time, and then later the total absence of variability. The orbit of the planetoid is highly inclined to that of the earth so that we view it under varying aspects, but in spite of this there are real difficulties in explaining the phenomenon.

One of the uses to which planetoids have been put is to obtain a very accurate measurement of the distance from the earth to the sun. The relative distances of the planets can all be found without knowing any actual distance. In Fig. 66 it was shown how the distance from the sun to Venus could be obtained in terms of the distance from the sun to the earth. In a similar way all the relative distances in the system can be determined. Then, if any actual distance either of a body to the sun or from one body to another can be found, all the distances become known. It is not easy to measure the distance from the earth to the sun directly because the sun is a body very poorly adapted for observation. In the first place, it is not a point of light and, indeed, has no absolutely sharp boundary. In the second place, the light and heat from it shining into the instrument disturb the delicate adjustments necessary for making accurate observations. In the third place, it is very far away and the difficulties of obtaining accuracy increase with the distance. But the first two objections to using the sun as a means of finding the distances of the members of the solar system from one another are absent in the case of the planetoids; and the third is also absent in the case of Eros. Probably the most exact method at the present time of finding the distances in the solar system is by measuring the distance of Eros. When this planetoid was near to us many observations of its position, both visual and photographic, were taken. Their reduction at many places, particularly at Cambridge, England, by Hincks, led to remarkably accurate results regarding the distance to the sun. It must not be supposed that our knowledge of this distance depends upon this method alone, for there are at least half a dozen others distinct from it. They all agree in about the same distance, though some of them give results which have a considerable degree of uncertainty.

Zodiacal Light and Gegenschein. The zodiacal light is a hazy wedge of light stretching up from the horizon along the ecliptic just as the twilight is ending or the dawn beginning. The base of it is from 20 degrees to 30 degrees wide, and it can be followed under favorable atmospheric conditions, when the moon is not in the sky, to a distance of 90 degrees from the sun. Sometimes a narrow, very faint band of light three or four degrees wide can be traced entirely across the sky. It is very difficult to determine exactly where the borders of the zodiacal light are, for it fades out very gradually into the darkness of the night sky, and at its brightest is not much brighter than the Milky Way.

The zodiacal light can best be seen when the ecliptic makes a large angle with the horizon, and this varies considerably at different times of the year. Suppose the sun is at the vernal equinox. It is then at the part of its orbit where the ecliptic crosses the equator from south to north. Suppose the sun is setting in the western sky. The equator comes up obliquely from the western point on the horizon and crosses the meridian at an altitude equal to 90 degrees minus the latitude of the observer. The ecliptic comes up from the western sky above the equator and crosses the meridian at an altitude 23.5 degrees greater than that at which the equator crosses. Consequently it comes up from the western sky more nearly perpendicular than the equator does. Since the sun is at the vernal equinox in the spring, this is the time of year when the zodiacal light can best be seen in the evening. When the sun is at the autumnal equinox the ecliptic crosses the equator from south to north and comes up from the western sky at sunset very obliquely, being south of the equator. At this time the zodiacal light is lost in the haze of the horizon and is not conspicuous. If it is desired to observe it in the morning, then it is found by similar discussion that the most favorable time of the year for seeing it is in the autumn, and the least favorable in the spring.

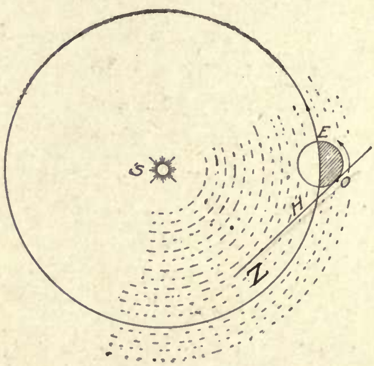


Fig. 76. The Zodiacal Light Is Due to Small Particles Revolving around the Sun near the Plane of the Earth's Orbit

The zodiacal light is probably due to a vast number of small particles revolving around the sun near the plane of the earth's orbit and extending out somewhat beyond the path of the earth. In Fig. 76 let *S* represent the sun, *E* the earth, and *Z* the particles of which the zodiacal band of matter is composed. Consider an observer at *O* for whom the sun has recently set. His horizon is *H*, and above *H* he will see part of the zodiacal band which is illuminated by the sun, and it will appear to him as a hazy wedge of light in the plane of the earth's orbit, that is, along the ecliptic.

Die Gegenschein, the German for counter-glow, is a very faint oblong patch of light on the ecliptic precisely opposite to the sun. It appears like an enlargement of the zodiacal band. It is so very faint that it can be seen only under the most favorable atmospheric conditions and in the absence of all artificial light. In fact, a planet or a bright star near it is enough to make it invisible, and the illumination of the Milky Way is absolutely fatal to seeing it. This faint object was not discovered until recent times when it was found independently by three observers, Brorsen, in 1854, and later by both Backhouse and Barnard. One theory for its explanation is that it is due to a large number of meteors circulating around a point opposite to the sun and about 900,000 miles from the earth. It can be shown mathematically that there is a point in this neighborhood at which a meteor placed and started suitably would always stay. If one were started near this point there would be a tendency for it to circulate around the point for a time and then to pass on. A stream of meteors passing around the sun and near this point would be caught in a sort of whirlpool and would circulate around it for a time, and give us just such a faint illumination of the sky as the gegenschein actually is. While this explanation seems very probable we are not absolutely sure that it is correct.

Probably the observation of the gegenschein is the best test of the power of distinguishing faint objects. It can not be seen through instruments, because with the telescope only a small part of the sky can be observed and no contrast can be obtained. This object is from 5 degrees to 10 degrees wide and 10 degrees to 20 degrees long. The best time for observing it is in the autumn months, September and October, when there is no moon in the sky.

Mercury and Venus. Having discussed the solar system as a whole and the planets in their relations to one another and to the sun, it is in order to consider them briefly as individuals.

Mercury and Venus, being inferior planets, are not situated very conveniently for observations because when they are nearest to us their dark sides are toward us. On this account the surface markings of these bodies are not so well known as those of the superior planets, some of which are not near the earth. Mercury can be observed best in the daytime. Many faint, dark lines have been noted upon it, particularly by Lowell. From a study of these he infers that the planet rotates on its axis once during its revolution around the sun. The fact that these streaks are visible shows that the planet has little or no atmosphere. When it passes between us and the sun it appears like a sharp disk on the surface of the sun, and this also proves the absence of any atmosphere. This result would be expected because the small gravitative power of this planet can not hold an atmosphere.

Another reason for believing that Mercury has no atmosphere is that its reflective power is very low. The observations show that it reflects only about 17 per cent of the light which falls upon it, which is about the same proportion as that reflected by the moon. Apparently a rough surface of broken rock reflects very much less light than an atmosphere, particularly if it is filled with clouds. Nearly everyone has noticed how extremely bright clouds of the thunder-head type sometimes are in the sky. These clouds appear very luminous because we see the light side of them. In most cases we are on the dark side of clouds, which gives us the impression that they are dull and non-luminous. The fact that it is dark below them proves that they either reflect or absorb a large part of the light, and that consequently if we were on the upper side of them they would appear very bright to us. As a matter of fact, the clouds are very highly reflective. Anyone who has seen clouds roll around a mountain peak knows how much brighter they are than the mountain unless it is covered with snow.

The climatic conditions of Mercury are most extreme, especially if one side is always toward the sun, as now seems to be the case. This side is exposed perpetually to the sun's burning rays at a distance where they are about nine times as intense as they are on the earth. The other side is never favored by its warmth and light. The one side is a region of perpetual torridity and the other of continual frigidity. There is a zone around the planet at which the sun is near the horizon, where the temperature is more moderate. In fact, all intermediate states between the hottest and the coldest exist. Almost certainly a planet in the state in which Mercury seems to be can not support life similar to that which flourishes on the earth.

Venus, as distinguished from Mercury, has an extensive atmosphere, as is indicated by its great brilliance, reflecting as it does 76 per cent of the light which falls upon it, and by the illuminated ring which surrounds it when it passes across the sun's disk. Furthermore, it follows from the kinetic theory of gases that, since Venus has a gravitative power at the surface nearly equal to that of the earth, it should hold an atmosphere as the earth does.

It has not been possible to detect many surface markings upon Venus because of the extensive atmospheric envelope which surrounds it. At the present time it is impossible to say even what its period of rotation is. Some observers have supposed they found evidence that it was approximately 24 hours and other observers have been equally convinced that their observations have shown them that it always keeps the same face toward the sun. If the former conclusion is correct the succession of day and night and the seasonal changes on Venus are very similar to those of the earth, though because of its nearness to the sun the climate should be warmer. If the latter conclusion is correct one side should be very warm—though not so hot as the corresponding side of Mercury—and the other side very cold. The reasons for the difference between Venus and Mercury in this respect are, *first,* that Venus is farther from the sun than Mercury is, and *second,* that the temperature of Venus would be largely equalized by the atmosphere. The warm air from the heated side would continually pass to the colder side, and the cooler air of the dark side back to the heated side. There would be a system of trade winds taking the heat from the hot to the cool side, and the cool air back to the heated side.

Mars. The planet Mars is at times situated more favorably for observations from the earth than any other celestial body except the moon. Its distance from the earth at its nearest approach is about 34,000,000 miles. At this time it is opposite the sun in the sky and appears on the meridian at midnight with the illuminated side toward the earth.

The reflecting power of Mars is low, implying in accordance with the discussion made above that it has a small atmosphere. Other observations confirm this conclusion. Its surface is nearly always well visible, showing rarely any indication of clouds. Probably the only clouds that are observed are dust storms.

The explanation for the scanty atmosphere of this planet is that its mass is so small and its surface gravity so feeble that it has not power to control one. If Mars does control an atmosphere, probably it is made up largely of the heavier gases. When Mars passes between us and a star the light of the star is suddenly extinguished as the edge of Mars reaches it. If Mars had an extensive atmosphere the light of the star would gradually diminish as it shone through more and more of the gaseous envelope surrounding the planet. Probably atmospheric pressure on Mars does not exceed that on the top of our highest mountains.

The planet Mars is at times so near us and it is so free from an obscuring atmospheric envelope that it has been possible for a long time to secure accurate observations of its surface markings. Fig. 77 shows a series of photographs (made by Barnard with the great 40-inch Yerkes telescope) of one side of Mars on which can be seen large shaded areas with a peninsular projection similar to that of the Indian Peninsula in southern Asia. The light-colored part of

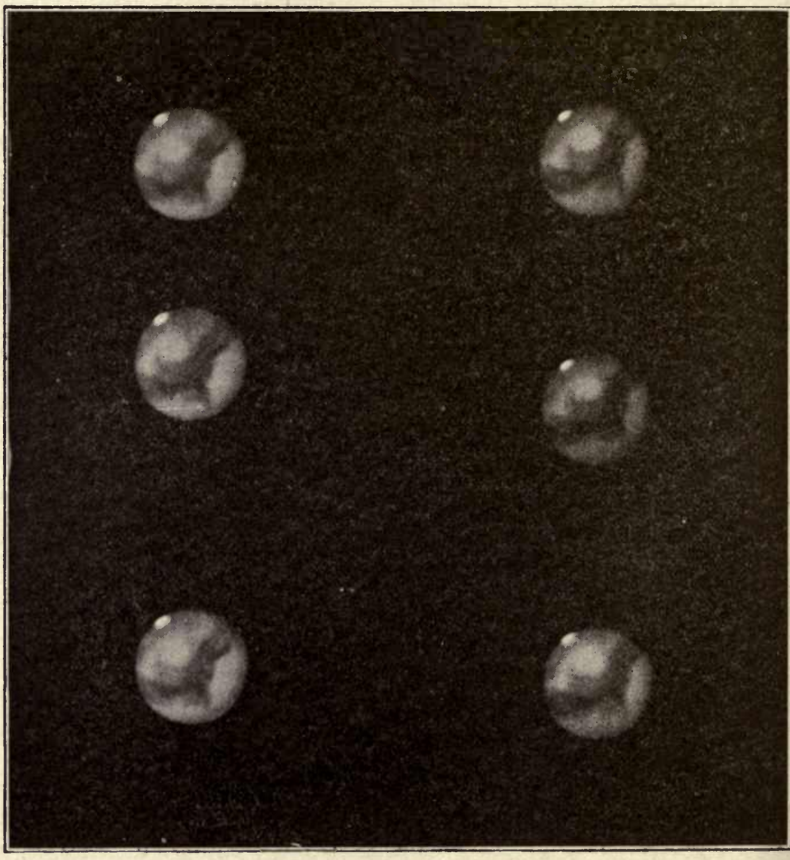


Fig. 77. Mars as Photographed with the Great Yerkes Telescope by Barnard

Mars is actually a sort of dull brick-colored red, and it is this which gives it its ruddy appearance in the sky. The shaded areas have a slightly greenish tinge. From observations of the motions of these markings across the disk of the planet it has been possible to find its period of rotation with a very high degree of accuracy, and also the inclination of its equator to the plane of its orbit. The day of

Mars is 24 hours, 37 minutes, 22.7 seconds long, reckoned in our mean solar time. The inclination of the plane of the equator of Mars to that of its orbit is about the same as the inclination of the ecliptic. Therefore, except for the greater distance of this planet from the sun, its days and seasons succeed one another about as the days and seasons of the earth run through their cycles.

Besides the dark-shaded areas observed on the planet, there are other remarkable details which have been seen in recent years. In 1877 Schiaparelli, an Italian observer, working with a modest telescope of 8.75 inches aperture, but favored with the transparent Italian skies, found that Mars was crossed and recrossed by many dark-greenish streaks which always began and ended in the dark areas mentioned above. These streaks were of great length and invariably extended in straight lines, that is, along the arcs of great circles. They varied from a few hundred miles in length up to nearly 4,000. These streaks were called by Schiaparelli *canali* (channels), which was unfortunately translated into "canals," a designation altogether too suggestive, for there is no guarantee that they have any analogy with canals on the earth. The very narrowest of them are 15 or 20 miles across, and when a number intersect at a point there is generally, if not always, a dark knot at the points of intersection. For example, seven canals converge in *Lacus Phoenicis* and six in *Lacus Lunae*. According to Lowell the junctions of canals are always provided with these spots, called "lakes," and conversely lakes are never found except at the junctions of canals.

In the winter of 1881-82 Mars was again in favorable position for observation and Schiaparelli studied it attentively a second time. He not only confirmed his preceding observations, but he found that in many cases there were two canals running parallel to each other for long distances. This doubling was found to depend upon the seasons and to develop with astonishing rapidity especially when the sun was at the Martian equinox.

The observations of Schiaparelli have been, in a general way, confirmed by Lowell and have been greatly extended by him during fifteen years of observations at Flagstaff and in Mexico with a telescope of 24 inches aperture. He has found in addition to the canals observed by Schiaparelli many others, bringing the total list now up to over 400. Lowell describes these streaks as very narrow and thread-like, and of remarkable uniformity. Fig. 78 shows the network of canals which Lowell discovered on Mars from many observations and recorded in a single drawing.

On the whole, other observers, many of whom have had wide experience and have been provided with large instruments, have not been able to confirm the observations of Schiaparelli and Lowell.

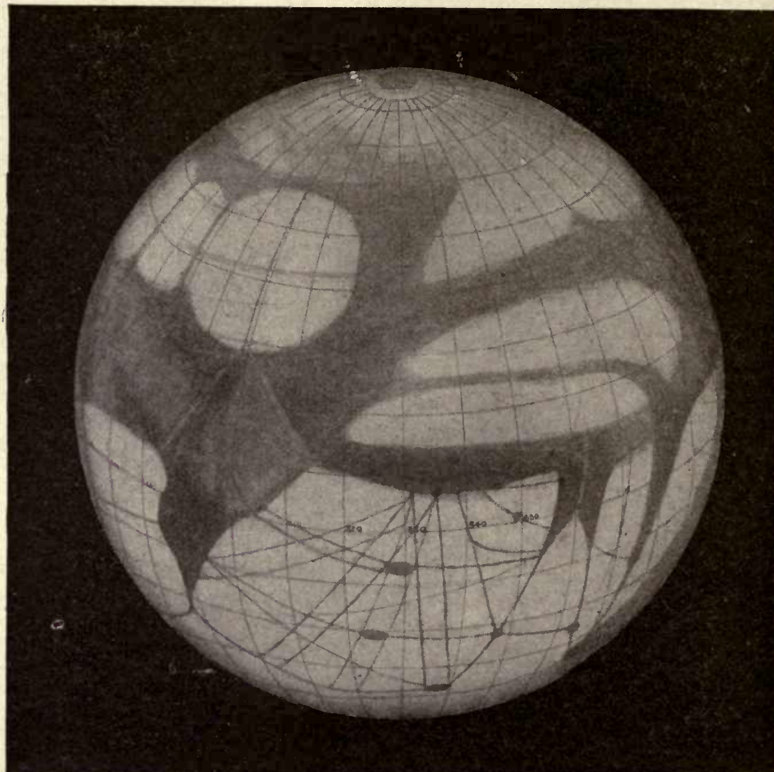


Fig. 78. Mars from a Drawing by Lowell

This negative evidence must be given considerable weight, though, of course, positive evidence should always be regarded as the more valuable. There have been many astronomers who have expressed the opinion that in some way the observers who have seen the line-like markings on Mars have been deceived, and that no such features exist there. Experiments have shown that if a number of small markings be placed irregularly on a disk, and the disk placed at such a distance that they are just beyond the limit of distinct visibility, then an observer seeing it will by some process integrate the fine markings into lines. Though lines do not exist on the object at which he looks, he will apparently see them under these circumstances. Because of this fact, the suggestion has been made that Mars is covered with a large number of fine spots which are slightly beyond the limits of dis-

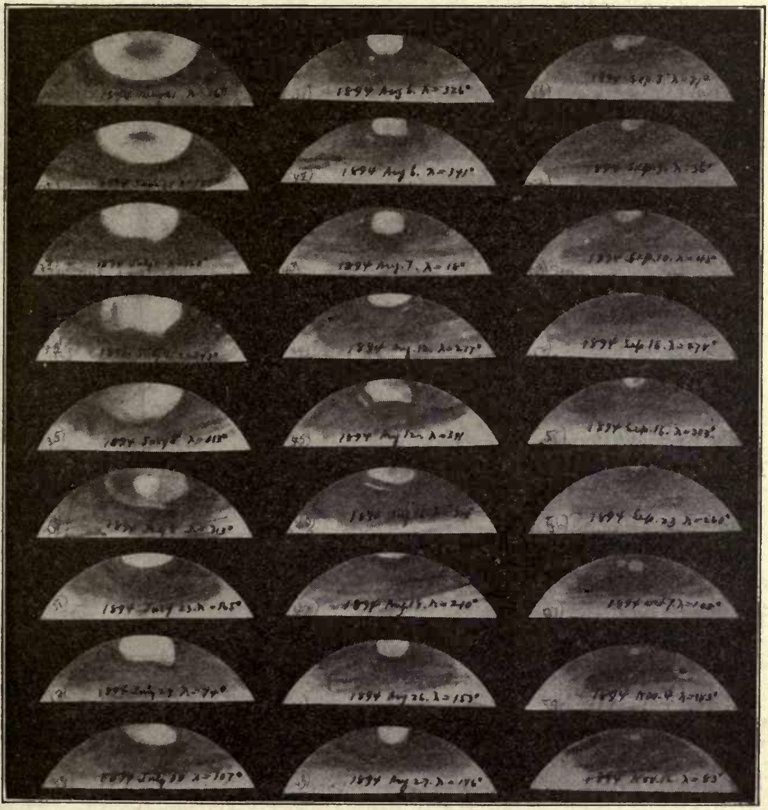


Fig. 79. The Disappearing Polar Caps of Mars as Observed by Barnard at the Lick Observatory in 1894

tinct vision and that the eyes, particularly of some observers, integrate them and give them the appearance of many lines. Of course, this conclusion is not a necessary consequence of the experiments.

Besides the canals on Mars, the most interesting other feature is the changing polar caps. When the autumn of a hemisphere of the planet comes on, the polar region extending down 25 degrees to 35 degrees from the pole is covered with a white mantle, shining with the brilliance of snow. This white covering appears suddenly, remains all winter, and disappears gradually in the spring, sometimes entirely vanishing at midsummer. It is entirely absent during the summer and reappears again rather suddenly in the autumn. Fig. 79 shows a series of drawings of the diminishing polar cap made by Professor Barnard in 1894 at the Lick Observatory. The slight irregularities in its outline prove at least a certain degree of roughness of the surface of Mars. While these polar caps have every appearance of being made of snow, there is some doubt whether this is the true explanation or not. In the first place, there is very little if any water upon the planet. In the second place, it is not perfectly certain that if there were water it would be transferred in clouds from one region to another and precipitated in the form of snow, though perhaps this is not an unreasonable conclusion. But the most serious question in the interpretation of these polar caps, is that apparently the climate of Mars ought to be considerably colder than that of the earth. Mars is so much farther from the sun than the earth is, that it receives less than half as much light and heat from the sun as the earth. Using this fact to compute the theoretical temperature which it would have if its atmospheric conditions were the same as those of the earth, and assuming that the mean temperature of the whole earth is 60° F., it turns out that the average temperature on Mars should be 38 degrees below zero. With such a temperature as this as an average for the whole planet, taking summer and winter together, it is clear we should not expect the polar cap entirely to disappear, inasmuch as on the earth it is a permanent feature. Of course, the different constitution of the atmosphere of Mars might account for a considerable difference, but it certainly would seem to strain the probabilities to suppose that a very rare atmosphere would have such a constitution that it could make a variation in the mean temperature of a planet of $60+38=98°$ F. And even this is not enough to account for the entire disappearance of the polar cap.

One suggestion made for explaining the polar cap of Mars is that it is carbon dioxide which freezes at a temperature of 109° F. If the atmosphere of Mars contains this compound, and if the temperature falls below this point, it would freeze and be deposited on the surface as a white substance resembling snow. But as was mentioned in connection with the discussion of the earth's atmosphere, carbon dioxide is one of the atmospheric substances which tends to produce a high mean temperature. It is thus apparent that this theory is at least to some extent contradictory to itself. At the present time we are not justified in drawing any positive conclusion about the meaning of the polar cap or the climatic conditions on Mars.

Assuming that the polar cap is snow and that the canals on Mars actually exist as they are seen by a few observers, the question of their explanation becomes one of considerable interest. W. H. Pickering suggested the idea that the canals are streaks of vegetation. This conclusion is to some extent supported by the fact that they appear in the spring, remain visible during the summer, and disappear in the autumn. Lowell pushes the theory much further by supposing that the canals are streaks of vegetation which grow because the territory where they appear is irrigated. This implies the existence of life and a high order of intelligence on Mars. He supposes that these intelligent creatures have dug waterways from the dark regions, which he interprets as being marshy regions, for hundreds and in some cases thousands of miles, out across the brick-red parts, which he interprets as being burning deserts. Leading out from the sides of these irrigation ditches he supposes there are lateral canals which reach to a distance of 10 to 25 miles. In this manner he supposes a streak from 15 to 50 miles wide and from a few hundred to three or four thousand miles long is irrigated. In the winter time vegetation would be dead, certainly if it were analogous to that on the earth, and the streaks would be invisible. As the spring approaches, the polar caps would melt and the marshy regions would fill up, the water would be led out through the main irrigation ditches and into the laterals, thus supplying the ground with the moisture necessary for the development of vegetation. Having then the increasing warmth and the needed supply of water, he supposes vegetation would spring up and flourish. This would give the areas on which it grew a dark color, as contrasted with the red of the soil. The places where the canals cross would be irrigated regions of unusual size and probably would be the seats of considerable population.

Lowell's theory is interesting, even if it is somewhat fantastic. There are serious difficulties in the way of accepting it, aside from the question of the climatic conditions on the planet. One of these is that it is not a sign of intelligence to construct canals thousands of miles long, in straight lines, and of uniform width, irrespective of the irregularities of the surface of the planet and the variations in the fertility of its soil. The irregularities of the borders of the polar cap prove that the surface is far from being smooth, and in fact the division of it into red regions and dark regions shows that it is by no means uniform. It is reasonable to suppose, in view of what we know of the earth and the moon, that all of it is more or less irregular. If it has had an origin similar to that of the earth, and if it has had an evolution similar to that of the earth, then the character of its soil should vary from place to place, like that of the earth. Certainly these are the probabilities. It seems most remarkable, then, that these creatures who are assumed to be intelligent should make their canals of absolutely uniform width and in absolutely straight lines. Besides, it is not evident why it is economical to run canals 3,500 miles from the source of water, when there is abundant unirrigated territory in the immediate vicinity. The expense of this is certainly enormous. If vegetation requires the same amount of water there that it does on the earth in order to flourish, the canal system and Lowell's interpretation of it imply that, for every ton of vegetable matter that is raised on Mars, on the average one thousand tons of water are transported along the canals one thousand miles. It is only fair to the reader to state that while Lowell has urged his views very strongly, astronomers are almost universally extremely skeptical regarding them.

Granting that Lowell's theory is correct, one is still likely to draw quite erroneous conclusions. If there is life on Mars and a high order of intelligence, there is no reason to suppose that the beings of highest intellectual development are physically anything like men. The animals on the earth, and human beings among them, are adapted to their surroundings, for if they were not more or less perfectly adjusted to them they would perish. For example, our skeletons are made of bones strong enough to support us and permit of certain activities when we are subject to certain gravitative forces; our lungs are adjusted to the atmosphere in which we live; and the amount of water on the earth and in its atmosphere is an important factor in the life processes, and animals on the earth are adjusted to these conditions. On the planet Mars nearly all of the fundamental conditions are radically different from those on the earth. For example, the surface gravity is much less, the atmospheric pressure is only a small fraction of what it is here, the constitution of the atmosphere may be quite different, the intensity of solar radiation is less than half that on the earth, and the amount of water is a very small fraction of that on the earth. Consequently, if life does flourish on Mars, then it must physically be very different from that on the earth. Of course, there is no fundamental reason why it should not be different.

Granting that there is life on Mars and that in its physical aspects it is suited to its environment, we are still likely to draw erroneous conclusions regarding the organization of what we may call its society. There is no reason for assuming that there are social and political conditions on another planet anything like those which are on the earth. If there is life there, thousands or millions of years ago it may have passed through that stage of evolution corresponding to the one in which we now struggle. When one thinks of the remarkable changes which society has undergone in a few centuries, the significance of such a statement becomes clear. At the rate human relations have been changing, in a few thousand years from now social conditions will be absolutely unlike those existing at present. Hence, it is clear that even though the physical conditions on another world were like those here, there would be no reason for assuming a general similarity in the mode of life and state of society.

Fig. 80. The Orbits of the Satellites of Mars and the Planet on the Same Scale

The planets Mercury and Venus have no satellites, so far as known, but Mars is attended by two very small moons revolving from west to east around it sensibly in the plane of its equator. They are so small and so near the bright planet that they were not discovered until 1877, when Hall found them with the great telescope of the Naval Observatory at Washington. They can be seen only with a few of the largest telescopes in the world. Hall named these satellites Phobus and Deimos. Phobus is 5,850 miles from the center of the planet, or only 3,750 miles from its surface. Deimos is distant 14,650 miles from the center of the planet. Fig. 80 gives the planet and the orbits of its two satellites to scale.

The diameters of the satellites of Mars are probably approximately ten miles. They are so small that they can not be measured directly, and can only be inferred from the amount of light they send us. On a body so small as these satellites and having the density of the earth, an object which would weigh one pound on the earth would weigh only $\frac{1}{60}$ of an ounce.

One consequence of the nearness of the satellites to the planet is their rapid revolution around it. The period of revolution of Phobus is 7 hours and 39 minutes, and that of Deimos 30 hours and 18 minutes. It follows from this that Phobus goes around the planet in about one-third of its period of rotation. Phobus and the planet both go to the east, but Phobus the faster. Therefore, the remarkable situation is realized of a satellite rising in the west and setting in the east. The period of Phobus from meridian around to meridian again is 11 hours and 7 minutes, or a little less than half a day. This satellite then runs through all the changes of its phases between sundown and sunrise. On the other hand, Deimos, whose period is longer than that of the rotation of Mars, rises in the east and sets in the west, the mean period from meridian to meridian being 131 hours 15 minutes.

Jupiter. Jupiter is a very bright object in the sky, its magnitude depending upon its great size and the high reflective power of its surface. When the computations are made it is found that Jupiter reflects about two-thirds of the sunlight which falls upon it. From this it can be inferred that it has an extensive atmosphere. This conclusion is supported by many other considerations. The mean density of the planet is very low and probably we never have seen its solid surface if, indeed, it has any.

As seen through a telescope Jupiter is characterized by a series of bright bands, alternately light and dull brown, running parallel to its equator. These bands vary in width and number, but are generally from 1,000 to 10,000 miles wide. They are most conspicuous near the equator, and the equator is generally covered by a light band. At the present time it is 8,000 or 10,000 miles wide. In 1882, according to the drawing of Hough, who for many years followed this planet carefully, the equator was entirely covered by a union of the dark bands which are on each side of it. Fig. 81 shows Jupiter as it has appeared in recent years.

One of the most conspicuous features ever seen upon Jupiter is what is known as the great red spot, which was until recently a pale pinkish oval extending parallel to the equator for 30,000 miles and in the opposite direction 7,000 miles. It appeared rather suddenly in 1878 beneath the southern red belt. In a year after its appearance it had changed to a bright red color, and was the most

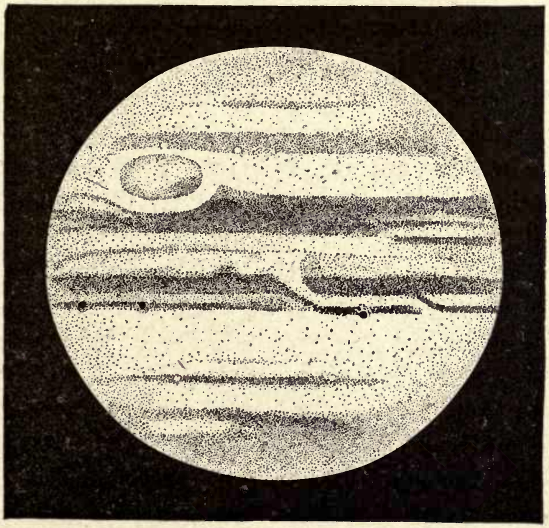


Fig. 81. The Planet Jupiter as Drawn by Barnard

conspicuous object visible on the planet. Since that time it has undergone many changes both of color and brightness, and though much diminished in intensity is yet generally faintly visible.

From observations of the spots and other distinct markings on Jupiter the period of its rotation on its axis has been found to be on the average about 9 hours and 54 minutes. No other celestial body is known whose period of rotation is so short as this. It is necessary to speak of the rotation on the average because there are great variations among the spots, particularly when they are in different latitudes. Some markings have been observed which give a period of 9 hours 50 minutes, while others give a period so long as 9 hours and 57 minutes, or an extreme difference of about $\frac{1}{85}$ of the whole period. And since the circumference of the whole planet is nearly 300,000 miles, it follows that the rate of rotation at the equator is about 30,000 miles an hour. Therefore, two spots whose difference in motion is $\frac{1}{85}$ the motion of either have a drift relative to each other of about 350 miles per hour. On the earth the most violent tornadoes we ever have are produced by wind velocities not much exceeding 100 miles an hour. The variation in the rate of rotation of the different parts of Jupiter is not entirely irregular. As a rule the equatorial parts rotate most rapidly. There are, however, some dissimilarities between the two hemispheres. On the whole the southern hemisphere presents evidence of more rapid changes in the spots, and perhaps greater relative motions among them. More remarkable than these variations in motion from spot to spot, is the fact that sometimes the rate of motion of a single spot changes considerably. For example, the period of rotation of the great red spot increased seven seconds in the first eight years following its discovery, but since that time it has remained sensibly constant. There is no conclusive explanation of the reason why the various zones of Jupiter rotate with different periods, or why the rates of rotation of the different spots vary from time to time.

It follows from the low density of Jupiter and the relatively rapid changes on its surface that there are probably no fixed features on it whatever. Probably this planet is largely gaseous, though the pressure at great depths is so great that it may be the laws of gases are not strictly obeyed. The surface gravity is 2.6 times that of the earth, and this indicates that there are enormous pressures in the depths of the planets. The fact that Jupiter has a low density in spite of high pressures, leads to the conclusion that either this planet is made up largely of very rare materials, or that it has a very high temperature. It has often been supposed that its surface is itself hot and partly self-luminous. One can scarcely escape this conclusion when he looks into the sky at Jupiter and sees how exceedingly brilliant it is. It stretches his imagination to believe that the light which he sees is all sunlight which has been reflected from the surface of the planet. Nevertheless, it is certain that Jupiter radiates directly no sensible quantity of light. As we shall see, this planet has many satellites and when they pass between it and the sun their shadows fall upon it. If Jupiter were self-luminous the places where the shadows strike would still be bright, the brightness depending upon its luminosity. But the actual observations show that where the shadows fall Jupiter is very black indeed. If the satellites should pass into the shadow of Jupiter, they would be still somewhat illuminated if Jupiter itself were luminous, but we find that if they pass behind Jupiter so that all the sunlight is cut off from them, they instantly become totally invisible. From this we conclude that, although the planet may be very hot throughout most of its volume, its surface is yet so cool that it gives out no sensible quantity of light.

The inclination of the plane of Jupiter's equator to that of its orbit is only three degrees. The eccentricity of its orbit is very small. Consequently there are no marked seasonal changes on this planet. Jupiter is a little more than five times as far from the sun as the earth is, and therefore gets less than $\frac{1}{25}$ as much light and heat. If it were situated similarly to the earth and had an atmosphere similar to that which surrounds the earth, its mean temperature would be extremely low. If planets go through an evolution from those primitive conditions in which we find Jupiter at the present time to those the earth is in now, and perhaps on to dead worlds like the moon, certainly Jupiter when it loses its heat will lapse into a condition of perpetual frigidity.

Jupiter is surrounded by a remarkable family of satellites. Four of them are large, ranging in diameter from 2,000 to 3,600 miles. They were the first celestial objects ever discovered with a telescope, and were first seen by Galileo in 1610. They are barely beyond the limits of visibility without optical aid and, indeed, could be seen with the unaided eye if they were not lost in the dazzling rays of the planet. No other satellite of Jupiter, besides these four, was discovered until 1892 when Barnard, then at the Lick Observatory, caught a glimpse of a fifth one very close to the planet. It is so small and so buried in the rays of the great planet that it can be seen only by experienced observers through a few of the largest telescopes in the world. Since 1905 three new satellites revolving at great distances from the planet have been discovered. Two are at a distance of about 6,500,000 miles from the center of the planet, and the third is distant about 12,000,000 miles.

The distances of the satellites range from 100,000 miles to 12,000,000 miles; the periods from about 12 hours to 550 days. The periods are much shorter than they would be for a planet of a smaller mass. For example, the satellite nearest Jupiter of the four which Galileo discovered, which is numbered 1 and named Io, revolves at a distance of 261,000 miles. This is a little greater than the distance of the moon from the earth, but in spite of this fact its period instead of being 27 days is less than 2 days. This is, of course, due to the greater attractive power of the planet Jupiter, and, as was explained above, gives us a means of determining the mass of Jupiter. Fig. 82 gives Jupiter and the orbits of the five inner satellites to scale.

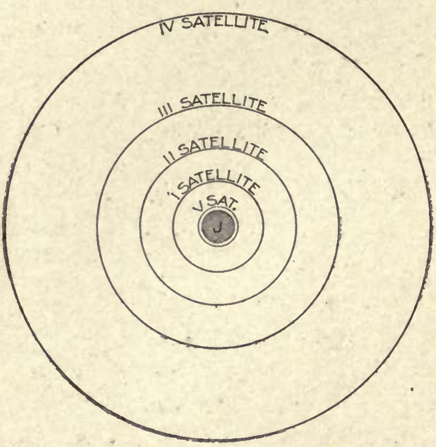


Fig. 82. Jupiter and the Orbits of Five of Its Satellites on the Same Scale

A very remarkable discovery was made in connection with Jupiter's satellites, in 1675, by the Danish astronomer Römer. The period of revolution of Jupiter's satellites can be determined from the times when they pass into the shadow of the planet and become invisible.

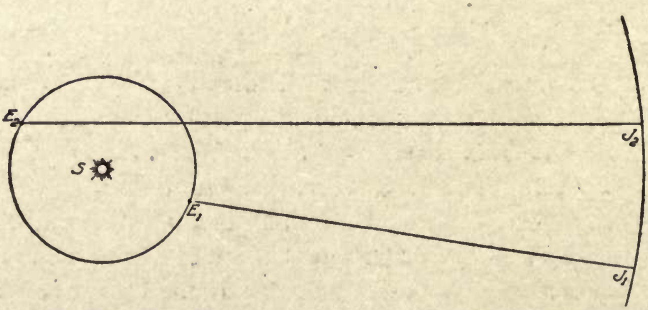


Fig. 83. The Discovery of the Velocity of Light from Eclipses of Jupiter's Satellites

Their periods were determined when the earth was on the side of its orbit towards the planet, as at E_1 in Fig. 83. Having determined the period, it was possible to predict the times when the eclipses should occur. A few months later when the earth got to the position E_2, and Jupiter to J_2, it was found that the eclipses did not occur at the predicted times, but a few minutes later. It was inferred from this that the reason they were delayed was not that the satellites moved around Jupiter with different periods, but that the light had farther to come to the earth. After the satellite passes into the shadow of Jupiter, it is still visible to the earth until the last light which leaves it before it passes into the shadow, reaches the earth. The distance from J_2 to E_2 is nearly 180,000,000 miles greater than the distance from J_1 to E_1. Consequently, if light does not travel with infinite speed, the eclipses should be as many minutes late when observed from E_2 as it takes light to travel over the difference of these distances. It was found from the calculations that the observations could be explained under the theory that light travels at the rate of about 200,000 miles per second.

The finite velocity of light has been proved in many other ways. It has not been necessary to appeal to celestial phenomena in order to determine its rate, but it has been measured on the surface of the earth by a number of experimenters. The work of Fizeau, Michelson, and Newcomb shows that the velocity of light is very nearly 186,330 miles per second. It follows from this that it takes light about 499 seconds, or a little more than 8 minutes, to come from the sun to us. Therefore, when anything takes place upon the sun it is not seen here until 8 minutes later. The distance of Jupiter is so great that it takes about an hour and a quarter for light to go to it from the sun and back to the earth.

Saturn. In many respects Saturn is the most interesting planet in the solar system. It is distinguished by a remarkable system of rings which surround it in the plane of its equator. Fig. 84 shows the general appearance of the rings according to a drawing made by Barnard. The extreme diameter of the outer ring is approximately 175,000 miles. Between the outer ring and the brightest one is a vacant space about 2,200 miles in width. This is known as Cassini's division, having been discovered by the French astronomer Cassini. Inside of Cassini's division is the brightest ring, whose width is about 18,000 miles. Near its exterior it is brilliantly luminous, shining as brightly as the planet itself, but it fades out gradually toward its interior border. Inside of the bright ring is a fainter ring known as the *crepe ring,* which was discovered simultaneously in this country and in England about fifty years ago. Its width is about 11,000 miles. Then between the inner edge of the crepe ring and the planet is a gap of about 6,000 miles.

The ring is very thin, as is shown by Barnard's drawing, Fig. 85, when it was almost edgewise to the earth in 1907. When it was exactly edgewise it became invisible even through the great Yerkes telescope. It follows from this that its thickness can not exceed 50 miles. If one should draw a map of Saturn and the ring system, making the whole diameter of the ring system five inches, on the same scale the thickness would be only $\frac{1}{700}$ of an inch.

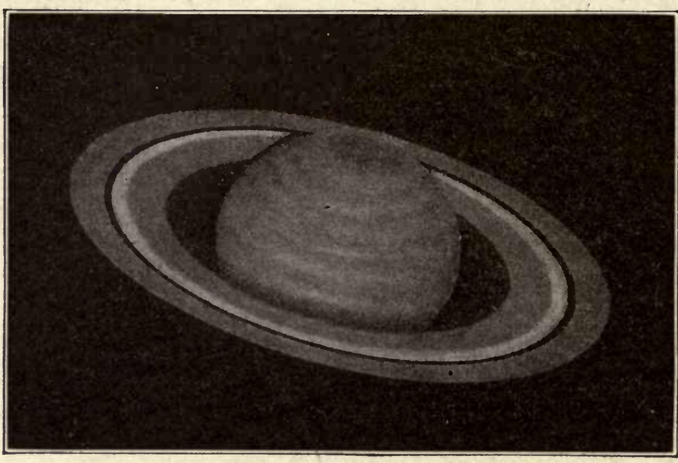


Fig. 84. Saturn and Its Rings from a Drawing Made by Barnard

The bright rings appear to be as solid and as continuous as the planet itself. For many years after their discovery by Galileo, it was supposed that they were perhaps composed of solid or liquid material. It was proved by Laplace that such a constitution is impossible. If they were solid the attraction of the planet would crush them unless they were made of stronger material than anything we know. It is easy to see that a solid ring is dynamically similar to an arched bridge, the difference being that the ends of it do not rest upon the planet but upon other portions of the ring. If the ring is supposed to rotate around the planet the difficulties are relieved to some slight extent. If it is supposed to rotate fast enough so that the centrifugal acceleration of the interior part balances the attraction of the planet for it, then the centrifugal acceleration of the outer part will be much too great and there will be a tendency for it to fly into fragments. Even if it were made of material a hundred times stronger than any material with which we are familiar on the earth, still it could not remain permanent in that form if it were in the solid state. A liquid state is equally impossible. Consequently there remains only one hypothesis, and that is that it is made up of a vast swarm of small particles circulating around the planet in the plane of the planet's equator. This theory was suggested nearly two hundred years ago but was not generally adopted until recent times. Under this hypothesis every separate particle moves like a satellite

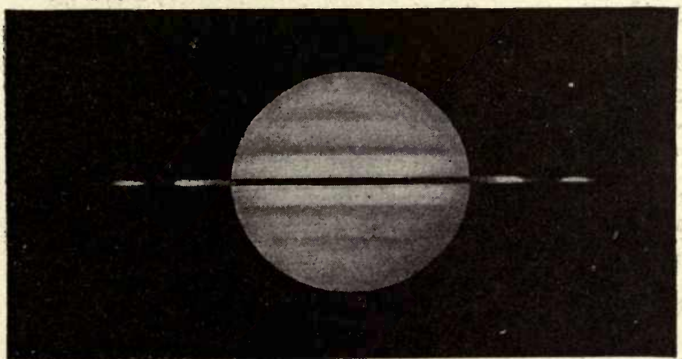


Fig. 85. The Rings of Saturn When They are Nearly Edgewise Toward the Earth—After a Drawing by Barnard

free from all the others except at times of possible collision. According to this theory those particles which are nearest the planet move most rapidly, and those which are farthest move most slowly, and the difference is a precise amount depending upon the attraction of the planet and the difference in distance. It is possible to compute theoretically what this difference should be. About 20 years ago the spectroscope was used to determine how these particles moved, and it was found that their motions were in perfect harmony with the theory that the rings are made up of a great swarm of small particles which revolve independently of one another.

It might be supposed that there are difficulties in accounting for the appearance of solidity of the rings of Saturn on the dust-cloud theory. One might imagine that they should be more nearly transparent than they are. But the incorrectness of this view is at once evident when we consider how opaque are the clouds in our own atmosphere. Clouds are made up of small drops of water in great numbers and form opaque screens, though often they are not more than half a mile thick. Consequently, it is easy to see how a swarm of dust particles, possibly as much as fifty miles in thickness, might have the appearance of being perfectly solid. With such a thickness it is not necessary to suppose the particles are very close to one another or that collisions very frequently take place.

The planet itself is somewhat similar to Jupiter, though the markings on it are less distinct. There is a bright equatorial belt and many slightly darker zones in the higher altitudes. The polar regions are generally darker than any other part of the planet. It has been difficult to find spots which are lasting enough and conspicuous enough to enable the observers to determine the period of Saturn's rotation. But those determinations which have been made show that this planet rotates on its axis in a little more than 10 hours. It is also similar to Jupiter in the fact that its equatorial zone rotates more rapidly than its higher latitudes. Likewise there are relative drifts of different parts at high speed. Some portions have been observed to pass by others at the rate of 600 or 700 miles per hour.

Since Saturn has a density considerably less than water one would not expect to find in it any solid material, at least near its surface. The changing and unstable character of the markings which are observed harmonizes perfectly with this conclusion. It is almost certain that Saturn is gaseous to a great depth, and perhaps throughout. The planet is certainly in an early stage of its evolution and will not become suitable for the existence and development of life until after it undergoes enormous changes.

The plane of Saturn's equator is inclined to that of its orbit by 27 degrees. For this reason the seasonal changes would be marked. But Saturn is so far from the sun that it receives only $\frac{1}{90}$ as much light and heat per unit area from the sun as the earth does. It follows that if its atmospheric constitution were anything like that of the earth it would be continually frozen, even in its equatorial regions, and consequently that the seasonal changes would not be important. But here, as in the consideration of all the planets, the constitution of the atmosphere is an important factor which must not be neglected.

Saturn has more known satellites than any other planet. The last two of the ten were discovered by photography. The one nearest to Saturn is distant from its center 117,000 miles; the one farthest is distant about 8,000,000 miles. Their periods of revolution vary from about 225 hours to 550 days. The periods are shorter than they would be for satellites revolving around the earth at the same

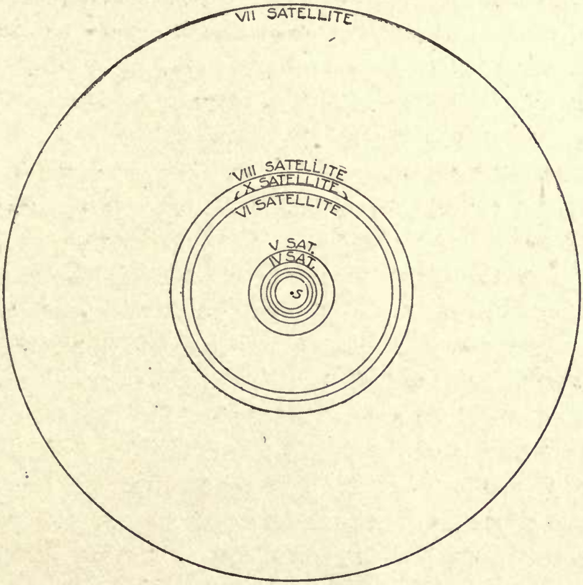


Fig. 86. Saturn's Satellite System, with the Exception of the Ninth, on the Same Scale

distances, but somewhat longer than they would be for planets revolving around Jupiter at the same distances. These satellites vary in diameter from 100 or 200 miles to 3,000 miles. Fig. 86 is a map of Saturn's satellite system (with the exception of the ninth which is so far away it can not be shown) in which the dot at the center represents the planet. A remarkable thing about these satellites is that all of them revolve from west to east with the exception of the ninth which revolves in the opposite direction.

Uranus. Uranus is so far from the sun that it appears in the sky as a faint object of the sixth magnitude. It was discovered in 1781 by Sir William Herschel, who was then carrying out his program of sweeping the whole sky for interesting objects. Herschel as a young man was a professional musician and originally took up astronomy only as a pastime. His imagination became fired by the mysteries of the heavens and he determined to explore them so far as was in his power. In those days it was not possible to buy a telescope for a relatively small amount of money, as it is now. Consequently, if he were to have an instrument he must make it himself. Accordingly, he took up the study of the theory of optical instruments and of other branches of mathematics and astronomy. With his own hands he made many telescopes. It was with one of these that he discovered the planet Uranus. One night in his sweeping of the sky he detected an object which, though nearly like a star, differed from a star in having a very small disk. Through a telescope, no matter how powerful it may be, the stars still appear as points of light, though, of course, much brighter than without an instrument. But the planets have sensible disks, their apparent size depending upon their actual size and their distance from the observer. Now, Uranus is so far away that its disk is apparently very small even when seen through a large telescope. It is remarkable that Herschel should have noticed that it differed in appearance from a star. At first he did not suspect that he had found a new planet. He informed his friends of the peculiar object which he had seen and expressed his opinion that it might be a comet. If it were not a star its position would change rapidly with respect to them. Observations showed in a few days that it was moving and in a few weeks that instead of being a comet it was, indeed, a new planet. This was the first world discovered in historic times. It immediately attracted the widest interest. George III., who was then king of England, appointed Herschel royal astronomer and he thenceforth devoted all his life to the study of astronomy.

Four satellites have been discovered revolving about Uranus. They all move sensibly in the same plane, which is almost at right angles to the plane of the planet's orbit. If the planet's equator is in the plane of the orbits of the satellites, as we may perhaps infer from analogy with the other planets, particularly Jupiter and Saturn, then the inclination of its equator to the plane of its orbit is about 90 degrees. A planet with such a relation of its axis of rotation to its plane of revolution would not have seasons in any respect similar to our own. However, this is not an important question in the case of a planet so far from the sun as Uranus is, because if the surface conditions and atmosphere are at all similar to those of the earth, its mean temperature must be many degrees below zero even at the equator.

Uranus is so far from the sun and the earth, being at its nearest to the earth about 1,600,000,000 miles away, that no surface markings have been detected on it by means of which its rotation can be determined. The only hope at present of finding its rate of rotation is from the effects of an equatorial bulge, which is a consequence of a rotation, on the motion of the satellites which revolve around it. These effects are so small that it is questionable whether accurate results can be obtained by them or not. Little is directly known regarding the physical condition of Uranus except its density. Perhaps an exception to this statement should be made because, when the light which is received from it is analyzed by the spectroscope, it is found that the atmosphere of Uranus has subtracted some of the light. The part of the light which is absorbed in this way depends upon the constitution of the absorbing gas. From a study of its light, made particularly at the Lowell Observatory, it is inferred that Uranus has an extensive atmosphere made up to a considerable degree of light gases. It is found from the observations that Uranus reflects about 60 per cent of the sunlight which falls upon it, and this also goes to support the conclusion that it has an extensive cloud-filled atmosphere.

Neptune. Neptune is the most remote planet from the sun, so far as is known, and is most inconveniently situated for observations from the earth. No surface markings on it have been detected and nothing is known regarding the character of its surface or the rate of its rotation. From its low mean density, high reflective power, and the character of the light its atmosphere absorbs, it is inferred that it has surrounding it an extensive atmosphere of light gases. It has one known satellite which revolves around the planet in a period of about six days and which has a diameter of about 2,000 miles. The plane of the satellite's motion is inclined to the plane of the orbit of the planet by 35 degrees, and it moves in the retrograde direction. If the satellite is in the plane of the planet's equator, and if the planet rotates in the direction of the satellite, it is the only example known of a planet rotating backward.

The discovery of Neptune, made in 1846, was the result of one of the most brilliant predictions ever made in science. Irregularities in the motions of Uranus led to it. As was explained in connection with the discussion of the planetoids, the orbit of a planet can be found from a few observations, and its position thereafter can be predicted for any length of time, however great. After Herschel discovered Uranus and had made a sufficient number of observations of it to enable mathematicians to compute its orbit, its theoretical position was calculated for many years. By 1820, or 40 years after its discovery, it was found that the planet was deviating a little from its predicted path. By 1830 the deviation was a little greater, and by that time had become sufficiently large to seriously disturb astronomers. This does not mean that mathematicians predicted Uranus would be seen in one part of the sky and that it was actually seen in quite another, but that the deviation was enough so that it could be observed with a telescope. As a matter of fact, the planet was actually observed so near its theoretical position that the difference was quite beyond the limits of visibility without a telescope. That is, if a star were in the predicted place and another in the observed place, the two would be seen as one without optical aid. The exactness of astronomical science is shown by the fact that so small a disagreement between theory and observation as this should have caused astronomers so much unrest.

The explanation of the discrepancy between theory and observation was not easy to make. However, shortly after 1830 a German astronomer, named Bessel, suggested that perhaps Uranus was deflected from its predicted path because of the attraction for it of an unknown planet situated out beyond it. The problem of finding the position of the unknown planet from so slight an irregularity as was observed in the motion of Uranus, was one of immense difficulty, and one which no one at the time had the courage to undertake to solve. The matter rested for about ten years and then two young men undertook the solution of the problem. One was Adams of Cambridge, England, and the other, Leverrier, of Paris. They began work on the problem, each entirely independent of the other, and without knowledge that the other was undertaking it. Adams finished his results first, in 1845, and found where the unknown world must be. He took his figures to English astronomers who had telescopes and asked them to search for it. He did not succeed in arousing any particular interest, nor in having active steps taken in the search. Being somewhat discouraged by the rebuffs he met, he let the matter rest. In the meantime Leverrier finished his computations by a different method, and arrived at essentially the same conclusions. He sent the results of his computations to a young German astronomer named Galle. The latter had the enthusiasm and the optimism of youth, and began the search the first night after receiving the letter from Leverrier. One can imagine with what impatience he waited for the sun to set and the stars to appear. When it finally became dark he turned his telescope to the sky and found, almost at the place Leverrier had predicted, within half an hour after he had begun his search, the unknown world. It is distant from the sun nearly 3,000,000,000 miles, and beyond all the senses except sight, and then can be observed only with optical aid. It had made itself known only through its effects on the motion of the planet Uranus, which had accumulated for a period of nearly 70 years. It is one of the triumphs of the human intellect that these men should have been able, with the instrument of analysis, to penetrate to such great distances and find with certainty the existence of a world which up to that time had been entirely unknown.

One might raise the question whether there are not still other planets farther out than Neptune. If there are, in the course of time they will make themselves felt by the disturbance of the motion of the planet Neptune. But since Neptune revolves around the sun only once in 165 years, it is clear that a very long time might elapse before they both came on the same side of the sun where these disturbing effects would be the greatest. Only 66 years have passed since the discovery of Neptune, and consequently the chances are rather against it having come in conjunction with any other planet farther out. At the present time there is no certain evidence of any disturbance in the motion of Neptune which can not be explained by the action of the planets so far known. On the other hand, there is no particular reason to suppose that there may not be other planets farther from the sun.

THE GREAT MOREHOUSE COMET
Picture taken October 30, 1908

ASTRONOMY

PART IV

COMETS AND METEORS

Orbits of Comets. Comets are wandering bodies which pass around the sun, usually in sensibly parabolic orbits. (See Fig. 67.) If their orbits are exactly parabolas it means they have come in from the sun from an infinite distance, and will go out again to an infinite distance, never to return. It is not possible to say that in any case the orbit is exactly a parabola, because the observations are made for only a short time while the comet is nearest the sun. It is clear from the common sense of the situation that under these circumstances the whole extent of the orbit can not be determined with perfect accuracy. A very slight error in an observation, which would make no sensible difference in the part of the orbit near the sun, might make a very great difference in the remote part. It is similar to the problem of determining a circle by means of three points. It is known from geometry that if three points not in a straight line are given, the circle through them is determined. If the three points are very near together the circle is poorly determined, especially in the parts remote from the three points.

While the statement is true that the great majority of comets move in sensibly parabolic orbits, and that it is not certain that they move in exactly parabolic orbits, there are certainly some which move in elliptical orbits. These comets come in from finite, though in some cases great, distances and go out again to the same distances. They return to the sun time after time, their periods of revolution depending upon the lengths of their orbits. There are a very few cases in which it seems that comets move in hyperbolic orbits, though there is some room for doubt regarding the conclusion.

If the comets, as a whole, move in parabolic orbits they can not be considered as permanent members of the solar system. On the other hand, if their orbits, instead of being parabolas, are very elongated ellipses they are permanent members of the system. The opinion seems to be growing among astronomers that the comets are actually in this sense permanent members of the solar system, though no rigorous proof of the statement is at present at hand. It has been seen that the orbits of the planets are all nearly in the same plane and that the planets revolve around the sun in the same direction. In the case of comets it is quite different. Their orbits lie in every plane and they revolve in all directions. There is no uniformity in their distribution. The only thing that can be said is that there is a tendency for the perihelia of comet orbits to cluster on the side of the sun which is ahead in its motion through space.

Dimensions and Masses of Comets. Comets consist of a head containing in it, usually, a small bright nucleus, and a long tail streaming out in the direction opposite to the sun. The head may vary anywhere from 10,000 miles up to more than 1,000,000 miles. The nucleus is generally a few hundred, and at the most a few thousand, miles in diameter. The tails are in length from a few millions up to more than 100,000,000 miles.

A remarkable thing about the head of a comet is that it nearly always contracts as the comet approaches the sun, and expands again when it recedes. On the contrary the tail increases enormously when the comet approaches the sun, and diminishes as it recedes. The nuclei of comets vary in size, but in an irregular fashion for which no law has been discovered.

The fact that the tails of comets point away from the sun is a matter of the highest interest. It is not very easy to explain precisely the reasons for this. One of the chief hypotheses so far advanced for explaining this phenomenon is that the sun exerts an electrical repulsion on the particles which come from the head and go off in space to form the tail. More recently it has been found both theoretically and experimentally that light exerts a pressure which depends upon its intensity and upon the surface of the body on which it falls. Light pressure is so feeble a force that it does not sensibly affect masses of large dimensions, but it can be an appreciable disturbing influence in very small particles. The general conclusion at present is that the tails are produced by electrical disturbances and that they project out from the heads of comets in the direction opposite to the sun because of electrical repulsion and light pressure.

Comets shine both by reflected light and by their own intrinsic brilliance. When they are far from the sun, *i. e.*, beyond the orbit of Mars, they are generally very faint and shine almost entirely by reflected light. As they approach the sun they become active internally and increase in brightness, not only because they are more brightly illuminated by the sun, but also because they become self-luminous in some way which is not fully understood.

Notwithstanding the fact that the volume of a comet is often very great, exceeding that of all the planets of the system and even that of the sun itself, yet comet masses are very small. This is proved by the fact that when they pass near planets, the planets pull them entirely from their paths by their attractions, while the comets do not in turn disturb the planets enough so that it can be observed. In fact, one comet passed through Jupiter's satellite system in 1886. This great planet and its satellites totally changed the orbit of the comet, but it in turn did not disturb even one of the satellites enough so that the changes in its motion could be observed. From these facts, chiefly, we infer the very small masses of the comets.

As a comet moves around the sun its mass is continually dissipated in space along its tail, as is illustrated in Fig. 87. The light, volatile materials held in its head and nucleus are evolved under the stimulus of the sun's heat and electrical activity, and are repelled out into space, never to return to it again. In the case of comets which move around the sun in closed orbits, this dissipation of material continues until they often become altogether invisible. There are now numerous examples of comets whose light has failed, apparently because of the dissipation of their luminous parts into space.

Capture of Comets. Suppose a comet comes into the solar system on a very elongated orbit, perhaps a parabola. If it does not pass near a planet it will go around the sun and out again on a curve of the same character. If it passes near a planet the orbit may be entirely changed, and the character of this change depends upon the circumstances of the near approach to the planet. Under certain circumstances the orbit will be reduced from an elongated one to one which is more nearly circular. In this manner a parabolic orbit may be reduced to an elliptical one. Jupiter, having a greater mass than any other planet and in fact greater than all of them

Fig. 87. Matter Receding from the Head of a Comet and Forming a Long Tail. Photographed by Barnard

combined, obviously will capture more comets than any other planet. Its chances are favorable also because of its location. If a planet beyond Jupiter should capture a comet, this orbit would still pass that of Jupiter and Jupiter in turn might capture it and reduce its orbit still further. But if Jupiter reduced the orbit of a comet so that its aphelion point were at approximately the distance of this planet, the planets farther out would thereafter have no sensible effect upon it. For these reasons Jupiter has a larger family of

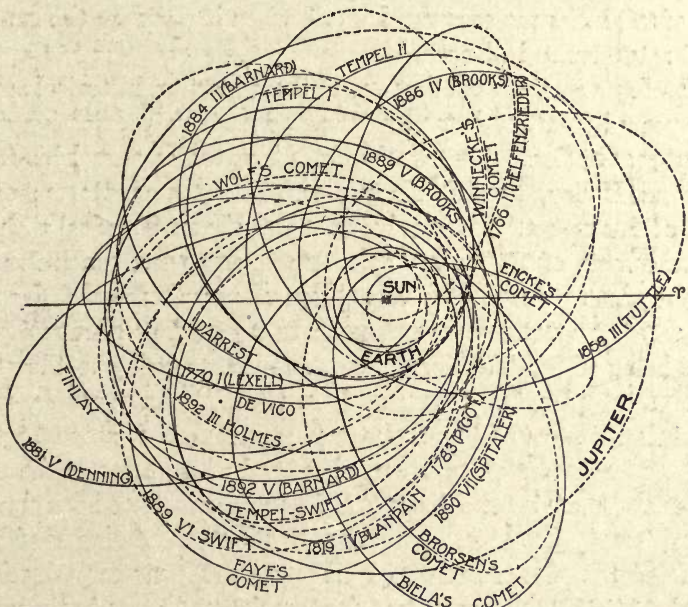


Fig. 88. The Orbits of Comets Which Have Been Captured by Jupiter

captured comets than any other planet. In Fig. 88 the small circle represents the orbit of the earth and the large circle the orbit of Jupiter. The ellipses are the orbits of those comets which belong to Jupiter's family. Some of them have now become invisible because of the dissipation of their material in space.

The planets Uranus and Neptune have small comet families, and there are other comets whose aphelia are still farther from the sun. Perhaps this may be considered as a reason for suspecting the existence of planets farther out than Neptune. The members of one small group of comets at their most remote distances, are about three times as far from the sun as Neptune is, and the other about ten times as far. Planets at those distances would revolve around the sun in the immense periods of 1,000 and 5,000 years respectively.

Celebrated Comets. Among the celebrated comets of historical times that of 1680 may be mentioned as being the one to which Newton's theory of gravitation was first applied. Its orbit was computed and it was found that it revolved in a long ellipse with a period of about 600 years. At its nearest approach to the sun it was only 140,000 miles from the sun's surface, and it moved at the rate of 370 miles per second. Its tail, when it was near the sun, was 100,000,000 miles in length.

Halley's comet is another one of the important historical comets. It appeared in 1682, four years before Newton's publication of the law of gravitation. After the work of Newton appeared his friend, Edmund Halley, applied his method to the computation of the orbit of this comet. He found that it was almost identical with that of the comets of 1607 and 1531. He came to the conclusion that these various comets were but different appearances of the same one, which revolved around the sun in a period of about 75 years, there being slight deviations from this number owing to the attractions of the planets. Going back in the historical records, it was found that comets had been observed at intervals of about 75 years, reaching back to a century or so before the beginning of the Christian era. There is little doubt that Halley's comet has been observed during twenty-five of its approaches to the sun. Halley confidently predicted that the comet would reappear and pass its perihelion on March 13, 1759. He recognized the fact that the perturbations of the planets and the uncertainties in its orbit might make his predictions of the time of its next approach to the sun slightly inexact. This was the first long range scientific prophecy. It was made in precise mathematical terms without the use of ambiguous language. The fulfillment or failure of it was awaited with great interest as the time drew near. When the year 1759 came the comet reappeared according to the predictions of Halley and passed the sun within a month of the time he considered most probable. Before that time there was no prophecy in all history made in so definite terms which was so literally fulfilled.

Halley's comet appeared again in 1835, when it passed within 5,000,000 miles of the earth. Fig. 89 shows the position of the orbit with respect to the earth's orbit and that of Neptune. After its appearance in 1835 it went out into space and quickly became invisible. For almost 75 years it was beyond the range of even the most powerful instruments, and was followed in its course only by mathematical processes. Though it could not be seen and its existence and position could not be proved by any direct processes, yet the perfection of astronomical theory is so great that those best qualified to judge never doubted for a moment that the theory indicated exactly where it was. It was known from the computations that it would appear again in 1910. The event is of so recent occurrence that everybody knows of its return, and that it passed the sun in perfect harmony with the predictions. The newspaper tales of the mysteries and peculiarities attached to it were pure fiction.

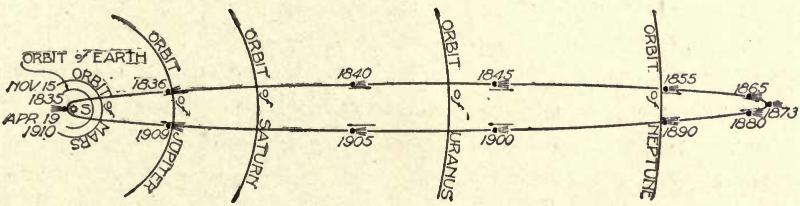


Fig. 89. The Orbit of Halley's Comet

Fig. 90 shows the relative positions of the comet and the earth during its time of nearest approach to the sun and the earth. On April 19 the comet was at its nearest approach to the sun, but was so far from the earth that it was not a very conspicuous object. On May 18 it passed between the earth and the sun and at this time was visible. Between the latter part of March and May 18 it was visible in the morning sky. After May 18 it became visible in the evening sky. The diagram, taking into account the direction of the motion of the earth and of its rotation, will show the reasons for this.

Encke's comet, discovered in 1819, is remarkable for the fact that it has the shortest known period (3.3 years), and also for the fact that its period was shortened during several revolutions without any known reason. It has been suggested that it was due to its encountering some resisting matter in the system, and that is probably the true explanation.

Biela's comet, discovered in 1826, revolves around the sun in a period of 6.6 years and is remarkable particularly for the fact that in 1847 it broke into two parts which gradually separated. Since 1852 it has not been observed.

The great comets of 1880 and 1882 were remarkable for their splendor, for the nearness of their approach to the sun, and for the fact that they moved in almost the same orbit. The orbits of these comets are very elongated and their period of revolution, if indeed their orbits are elliptical, must be several hundred years

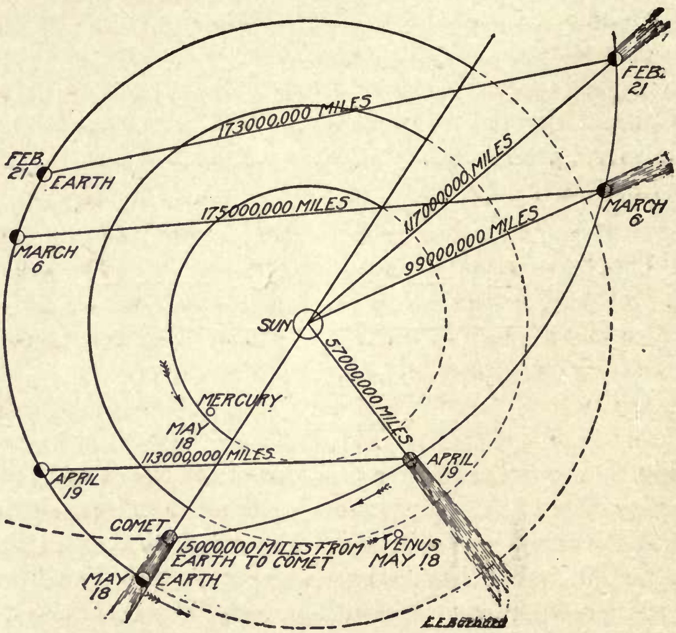


Fig. 90. Path of Halley's Comet Showing nearest Approach to Earth

Consequently, the two objects can not have been the same one. They were simply two bodies moving in almost the same paths. Other comets moving in the same orbit, at least approximately, were those of 1668 and 1843, both of which were brilliant objects. These comets either have had a similar origin, or are fragments of a once greater comet which has been broken into a number of pieces in some transit through the solar system.

Meteors or Shooting Stars. An attentive watch of the sky on almost any clear evening for a little while will show one or more so-called shooting stars. They are little flashes of light which have the appearance of being a star darting across the sky and disappearing. Since to call them shooting stars is a little misleading, we shall always speak of them as meteors. Instead of being actual stars, they are as a matter of fact tiny masses of matter, so small that one could hold them in his hand, which are moving in space in the vicinity of the earth. Under certain circumstances of motion and position they dash into the earth's atmosphere with a velocity which usually lies between 10 and 40 miles per second. The heat generated by friction with the air of bodies moving with this high speed burns them up. The products of their combustion and pulverization fall to the earth, or are added to the atmosphere.

The height of meteors is obtained from observations of them at two different places. These observations at the same time give the lengths of their luminous paths. If their brightness is also measured and the time which they are visible, it is possible to compute the whole amount of light which they radiate. This radiant energy depends upon the mass of meteorite and its velocity. The velocity being known, the mass remains the only unknown and can be computed. It is in this way that it has been found that the masses of meteors are very small, usually being only a few grains.

The numbers of meteors are much greater than one might imagine when he finds that generally he can see only a few in watching an hour. The reasons are that he can not see the whole visible sky at one time, and that only a small part of the earth's atmosphere is within the range of his vision at one time. If a circle is made to represent the earth and the atmosphere is put on it to scale, it will be clear why an observer can see so small a part at once. Accurate count of the numbers of meteors visible in a given time, made by many observers, and computations to extend the numbers so as to include all that fall on the whole earth, show that from 10,000,000 to 20,000,000 strike into the earth's atmosphere daily.

Meteors strike into the earth's atmosphere from every direction, but more are received on the side of the earth which is ahead in its motion around the sun than on the side which is behind, for the side which is ahead receives not only those which meet the earth but also those which the earth overtakes, while the part behind receives only those which overtake the earth. It is found that those on the side ahead strike with greater velocities than those received on the part behind, as would, of course, be expected from the nature of the case.

The part of the earth which is ahead is that which is on the morning side of the earth. In Fig. 91 let *S* represent the sun, *E* the earth, and the arrows the direction of rotation and revolution of the earth. The point *O* is at the sunrise line and is on the side of the earth which is ahead in its motion around the sun.

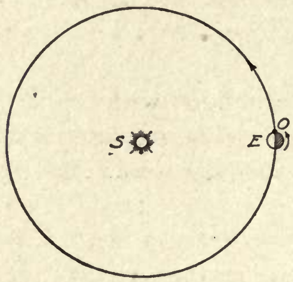


Fig. 91. The Earth Encountering Meteors in Its Revolution Around the Sun

Relation of Comets and Meteors. As the volatile matter which goes to make up the tails of comets is dissipated in space, there is left behind only the denser particles which make up the head, or perhaps the nucleus. These denser particles continue to revolve around the sun indefinitely unless the planets disturb their orbits so that they recede to infinite distances, which is a possible occurrence, or unless they are swept up by the planets. If a planet should strike the remains of an extinct comet it would encounter a swarm of particles moving in sensibly parallel directions and with equal speed. If these particles were small they would produce a meteoric shower.

Observations show that there are many meteoric showers. Particles moving in sensibly parallel lines strike into the atmosphere at various times of the year. In some cases the orbits of these particles around the sun have been determined. One of the most celebrated known cases, and one which has given the most remarkable meteoric showers, is that of the meteors which the earth encounters on November 14. They move in an elongated orbit of which they make the circuit once in 33 years. They have been moving so long in the orbit that they are scattered more or less thickly along its whole length, but they are more numerous at a certain place than elsewhere. Once in 33 years the earth passes through this nucleus. The swarm of meteors and the earth move in opposite directions, and consequently the earth meets these meteors on its morning side. They appear to come out of the constellation Leo, and are hence called Leonids. They are almost certainly the remains of a comet which was captured by the planet Uranus in 126 A. D.

This conclusion is based on the computation of the present position of their orbit and tracing it back until it was found that at this date the meteors and Uranus were very close together, and in such a relative position that Uranus would reduce their orbit from a parabola to an elongated ellipse in which the comet would move in a period of 33 years.

In 1833 the first known remarkable encounter with this swarm was experienced. Then, as seen from some places, the sky was filled with thousands of meteors. At that time the explanation of a meteoric shower was not known. But in 1866, on the same day of the same month, a similar meteoric shower was observed. Following this the theory of the phenomenon was fully worked out.

There are many meteoric showers, though they are on the whole less conspicuous than the Leonids. There is a shower visible yearly on November 24, in the constellation Andromeda, and other conspicuous ones occur on April 20 and about the 10th of August. It is supposed that all these meteoric showers are produced from the remains of disintegrated comets. If so, we see how slight the masses of the comets are, and how little we should have to fear even though one were headed toward the earth and a collision were certain.

Influences of Meteors on the Earth. It might be supposed that objects so small as meteors would have no sensible effect on a great body like the earth, and such is the case if only a short period of time is under consideration. But in astronomical and geological science the earth is considered not only for years and centuries, but for millions of years. Though the effects of meteors are insensible for years or even centuries, it may be that in the long run they are very important. Sometimes those influences which, though small, work continually in one direction are the most important. For example, the washing down of mountains and hills and plateaus by running water is not a matter of any consequence for a short time, but when considered during the vast ages of the geological changes this is one of the most important agencies in transforming the earth.

One effect of meteoric matter circulating around the sun is to resist the motion of the earth a little. This resistance has a slight tendency to decrease the size of its orbit and to bring it nearer and nearer to the sun. In a similar manner the resistance also slightly retards the rotation of the earth and thus makes the day longer.

Another effect of the sweeping up of meteoric matter by the earth is that the earth's mass in this manner continually grows. It is conceivable that the earth has been revolving around the sun long enough to make this a very important factor in its evolution, and it is also conceivable that in former times the rate at which meteoric matter was acquired was much faster than at the present time. An indirect effect of the growth of the earth is that because of its greater gravitative power it slowly though slightly winds in toward the sun. No calculations are at hand which enable us to give any precise estimate of the effects of these causes upon the evolution of the earth.

Meteorites. Now and then large bodies, weighing from a few pounds up to a few tons, dash into our atmosphere and plunge down through it in a few seconds and strike the surface of the earth with great violence. Those bodies whose masses are so great and which are solid enough to last until they strike the surface of the earth, are called *meteorites* in contrast to those which are burned up in the atmosphere and which are known as meteors. The meteorites are generally composed largely of rocky material, though they are often mixed with some metallic iron. When pure iron is not found its compounds are usually present. About three or four per cent of the meteorites which fall are almost pure iron mixed with a little nickel. Altogether about thirty of the eighty elements known on the earth have been found in meteorites, but no new substances. Yet the structure of meteorites is quite different in some cases from that of any minerals found on the earth, and from an examination of them it can be proved that they are of extra-terrestrial origin.

Some meteorites show evidences of remarkably perfect crystallization; others show places where they have sometime been fractured and later cemented. Sometimes at the fractured place one part has slipped slightly on another before they were again joined in a solid mass. These facts are very important in connection with theories regarding their origin. The very perfect crystallization, as well as the fractures and re-cementation, indicate strongly that these bodies are fragments of large masses of world-like dimensions. If so, they are not masses ejected from the sun or by volcanoes from the earth and moon, for in those cases they would cool quickly and be glassy rather than crystalline, and there would be no chance for fractures and re-cementation. Chamberlin has suggested that probably they are fragments of planets which once existed before the origin of our present system.

THE SUN

Light and Heat Received from the Sun. It is a matter of common observation that the sun furnishes the earth an enormous amount of light. Compared to full sunlight, almost any artificial light used for illumination seems dull and feeble. Even when the sun's rays are largely cut off by clouds, the illumination of a room or building is generally much greater than it is at night with the artificial lights which are ordinarily used. A direct measurement of the intensity of sunlight shows that it is 60,000 times that of a standard candle at a distance of one yard.

Light is a wave motion in the ether in many respects similar to sound waves in the air, though there are some fundamental differences. Sound waves to which the ear is sensitive vary in length from approximately an inch to many feet. Light waves to which the eye is sensitive vary in length from about $\frac{1}{39,000}$ of an inch for the red to about $\frac{1}{62,000}$ of an inch for the violet. The longest waves are less than twice as long as the shortest ones. In the terminology of acoustics, our eyes are sensitive to less than one octave of light. while our ears are sensitive to ten octaves of sound. There are vibrations in the ether shorter than violet rays and others much longer. Those which are shorter than the violet rays are known as the *ultraviolet*, or chemical, rays, and those which are longer than the red rays are known as the *infra-red*, or heat, rays. From the standpoint of physics all of these rays are similar, and for short we may term them altogether radiant energy. The heat waves raise the temperature of a dark object on which they fall, and so also do both the light waves and the chemical waves. It follows that in considering the light and heat received from the sun we may group all of it together and treat it as a single type of energy.

It is possible to measure directly the radiant energy received from the sun at the earth's surface. The difficulty in measuring how much is actually received by the earth arises from the fact that it is hard to determine how much is absorbed in passing through the atmosphere. But by making observations at the sea level and again on high mountains, and taking into account the difference in the amount of air which the energy has passed through at the two positions, it is possible to get a tolerably accurate estimate of the absorbing effects of the atmosphere. In describing the energy received from the sun we may express the quantity in various units, as for example, the calory used by engineers, or the horse-power, which is in more common use. Everyone is familiar with the fact that heat energy is equivalent to work, and an example of its transformation is in the steam engine where the heat, generating steam, does work by means of the steam engine. The unit of work known as the horse-power will raise 33,000 pounds one foot high in one minute. Observations show that the radiant energy received from the sun on every square yard exposed perpendicularly to its rays is equivalent to three horse-power. The earth's surface is four times the area of a circle whose diameter is equal to that of the earth, and consequently the average amount of energy received per square yard on the whole earth's surface is three-fourths of a horse-power. It follows from this that, if the energy which falls from the sun on a manufactory could be used for mechanical purposes, it would run all the machinery within it. But it is not possible to use more than a very small fraction of the sun's energy for the purpose of doing work.

Notwithstanding the fact that the sun's energy is not directly available as a source of power, it is worthy of note that almost all the energy which we use has been derived indirectly from the sun. A former important source of energy was the wind which drove thousands and thousands of windmills, and pushed boats over the seas. The energy of the winds is entirely due to the sun. The winds blow because the sun heats up the equatorial zone of the earth more than it does the higher latitudes.

Another source of energy which was formerly more important relatively than it is at present, was the water power. The energy given up by the waterfall was indirectly derived from the sun; the sun's heat raised the water in the form of vapor from the oceans and lower levels into the atmosphere, and the winds carried it in many cases thousands of miles out over the land where it fell as rain or snow on the mountains and in the higher altitudes. Running down from the higher places and uniting into rivers, it became a practical source of energy where it plunged over precipices. The original rain may have fallen from an altitude of a half-mile or a mile, while in the waterfall we generally use a fall of not many feet, and in extreme cases not more than a hundred or so. It is obvious from this how small a fraction of the energy of the falling water could be utilized even if every waterfall in the world were used to the extreme limit.

The amount of energy in the falling water can be seen from the number of tons which descend in a heavy rain. While an inch of water is a very heavy rain, yet this amount often falls in a few hours. Since the weight of a cubic foot of water is 62½ pounds, a little computation shows that, in an inch of rain on a square mile, more than 60,000 tons fall from the sky to the earth. In a large part of the United States the annual rainfall is about 30 inches, or in round numbers 2,000,000 tons per square mile. Remembering that in North America alone there is a territory of at least 1,500 miles square where the average rainfall is about 2,000,000 tons per square mile, one gets an idea of the enormous energy the sun has put forth in evaporating the water of the oceans and raising it into the air. Clearly, this is an extremely small fraction of the solar energy which falls on the earth.

The most important source of energy at the present time for mechanical purposes is undoubtedly coal. The coal had its origin in plant life which flourished ages ago. Consequently, the energy which the coal gives off when consumed in our furnaces, was originally derived from plants. Now, the plants get their energy from the sun. The little cells in the leaves and stems are minute laboratories where the sun does work and where its energy is stored up. It is, of course, true that the plants live to some extent on the earth and water, but an examination of their constitution shows that it is a fact that almost all the energy which is stored up in their fibers has been derived from the sun. Consequently, when one sees a railway train driven by the coal which is fed into its furnace, he is seeing it pushed indirectly by energy derived from the sun. It follows from the fact that the plants receive their energy almost entirely from the sun that the animals, which live upon plants, receive their energy almost entirely from the sun. As a matter of fact, almost all the motions and activities which come under our observation, except the motions of the heavenly bodies themselves, are due to energy derived from the sun.

The earth, as seen from the sun, would be a very small point in the sky, about as large as Mars appears from the earth. The sun radiates heat and light into space in every direction. Consequently it follows that the amount of light and heat received by the earth from the sun is only a very small fraction of the whole amount radiated. It is approximately $\frac{1}{1,000,000,000}$ of the energy poured out by the sun. This means that the sun's surface is radiating heat and light at an enormous rate. The computation shows that on the average 140,000 horse-power are continuously radiated from every square yard of the sun's surface. In order to generate this enormous energy a layer of anthracite coal 25 feet thick would have to be consumed every hour. No blast furnace so far devised could develop energy at this enormous rate. Expressed in other terms the heat of the sun would melt a layer of ice 4,000 feet thick every hour over its whole surface.

It is a certain inference from the great rate at which the sun radiates heat that its temperature is very high. It is not easy to measure the exact temperature, *first,* because it is higher than can be produced upon the earth, and *second,* because there is no one layer of the sun which alone radiates light and heat. The high layers radiate vast quantities and in turn absorb much from the lower layers, which are also radiating. The higher layers are undoubtedly of somewhat lower temperature than the lower layers. But all recent determinations agree in showing that the temperature of that part of the sun which radiates light and heat into space is in the neighborhood of 10,000° F. This is several thousand degrees above the highest temperature so far obtained in the most powerful electrical furnace, and is sufficient not only to melt but also to volatilize all substances known on the earth.

Source of the Sun's Heat. Since the sun is pouring out an enormous quantity of energy into space, it would cool off in the course of time unless its heat were in some way replenished. Of course, since it is a very large body it would not cool off quickly. And the rate at which a body cools off depends not only on its size and mass but also upon its constitution. For example, a rock of a given weight will cool off more quickly than the same weight of water; or expressed otherwise, it takes more heat to raise the temperature of a given weight of water than it does to raise the temperature of the same weight of rock to an equal degree. In fact, more heat is required to raise the temperature of a given mass of water a certain number of degrees than of almost any other known substance. Now, if we assume that the sun cools off as slowly as water, we can compute how fast its temperature will fall since we know how fast it radiates heat. The computation shows that if the sun's heat were not kept up by some process, its temperature would fall about four degrees per year. Consequently in 3,000 years it would become cold. This proves that in some way the sun's heat is continually being restored.

We are accustomed to associating heat with fire, and it seems perfectly natural to imagine that the sun is a great place of conflagration, or a sort of furnace. Now, the combustion of a definite quantity of coal produces a definite quantity of heat, and it is easy to see that one can calculate how long the heat of the sun would be maintained if it were made of pure coal and oxygen, and if the heat were due entirely to the burning of the coal. It is found on making the calculations that, according to this theory, the heat of the sun would be maintained only about 1,000 years. The theory is clearly inadequate to account for the facts.

About 1850 a new principle in physical science, known as *the conservation of energy,* was developed. In brief it is that the total amount of energy in the universe does not change. It may change its form but not its quantity. For example, if a body is in motion it has a certain amount of energy called kinetic energy. If it strikes something and is stopped its kinetic energy is destroyed, but it is found that in place of the kinetic energy its temperature has been raised by the impact. Also some energy has been given forth as sound. But neglecting the sound and all the energy except that which is manifested in the increased temperature of the body, it is found that its increase in temperature is exactly equivalent to the kinetic energy it had, and that it can be transformed again into kinetic energy. It has been found that a body falling, subject to the earth's gravity, 772 feet has so much energy of motion when it strikes that its temperature is raised 1° C.

Following out the idea of falling bodies, it was suggested about 1850 that the sun's heat might be due to the impact of meteors falling in upon it. Because of the great gravitative power of the sun, a meteor would strike its surface with a velocity of about 480 miles per second. The quantity of heat generated by a body striking the sun at such an enormous velocity would be thousands of times that produced by the combustion of any mass of equal weight. But when the computations were made to determine the quantity of meteoric matter which would be required to keep up the enormous radiation of the sun, it was found that it was so great that in its passage among the planets it would not only seriously disturb their motions, but would sensibly raise the temperatures of the planets themselves by striking in upon them. If this meteoric matter came from space beyond the planets it would produce on the earth about $\frac{1}{231}$ as much energy as is received from the sun. Since this is millions of times as much energy as we receive from the meteors, obviously the theory is not quantitatively sound.

Almost at the time of the development of the meteoric theory a very remarkable contribution was made to the subject by the great German physicist, Helmholtz. He saw that if the sun were slowly contracting, the contraction would elevate the temperature of the sun and restore its heat. A contraction of a body is equivalent to a small fall of all of its particles towards its center. While at first thought one might suppose this would be quantitatively insufficient, yet the computation shows that, because of the enormous volume of the sun, an annual contraction of about 180 feet in the sun's radius would account for all the heat and light it radiates. So small a contraction on so large and distant an object as the sun would not become visible with even our best instruments until it had continued more than 6,000 years. In 1870, Lane showed that a gaseous body radiating heat into space would necessarily contract, and that in contracting its heat would not only be restored but its temperature would actually rise so long as it remained gaseous.

According to the contraction theory, which is quantitatively very much more satisfactory than any earlier one, the sun was larger in the past than it is at present, and in the future it will become continually smaller. This enables us to compute how long the sun can have radiated light and heat sensibly at its present rate. In making the computation for its effects on the earth, we do not need to follow it back beyond the time when it extended out to the earth. The computation shows that if the contraction theory is correct, and if the shrinking of the sun is the only source of its energy, then it can not have radiated light and heat on the earth at its present rate more than about 20,000,000 years. If this is the whole story, the series of changes through which the earth has passed and the evolution of plants and animals which live upon it have taken place inside of 20,000,000 years. Turning to the future, we can calculate how long it will be before the density of the sun will become so great that further contraction will be impossible. Assuming that it will not contract further when it gets as dense as iron, it follows that the future existence of the sun as an efficient source of light and heat will extend over only 8,000,000 or 10,000,000 years.

The contraction theory of the heat of the sun certainly is sound, and until recently was supposed to be the only source of the sun's energy. On the basis of the computations just mentioned, physicists and astronomers made rather definite statements of the age of the earth and the period during which evolution on its surface could have taken place. The geologists and the zoologists on the basis of data in their own sciences came to the conclusion that the earth has been undergoing an evolution much longer than 20,000,000 years. They were by no means in harmony on the matter, for their estimates ranged all the way from 50,000,000 to 500,000,000 years. Recently we have found reasons for believing that perhaps there are other important sources of heat in the sun. Since the discovery of X-rays and radium it has been found that certain kinds of matter undergo disintegration. That is, certain large molecules such as those of radium and uranium break up into molecules of smaller weight, and in the process of disintegration give forth enormous quantities of energy. The amount of energy is of the order of 1,000,000 times that produced in the combustion of equal weights of any known substance. One of the products of disintegration of radium is helium. Now radium is not certainly known to exist in the sun, but helium is extremely abundant there. In fact, helium was first known in the sun, and its name comes from the Greek word for sun. The fact that helium is abundant in the sun, perhaps can be interpreted as indicating that radium is there and has been undergoing disintegration. It is certainly possible, therefore, and indeed probable, that an important source of the sun's energy is the disintegration of matter. It is well within the bounds of possibility that this is the most important source of its energy. At the present time there is no reason to conclude that the sun has radiated light and heat at its present rate for only 20,000,000 years. The period may just as well be 10 or 50 times as long. Similarly, there is now no reason to suppose that in 8,000,000 or 10,000,000 years in the future its light will begin to fail. While no positive statements can be made regarding the matter, it does not seem, in the light of our present knowledge, unreasonable to suppose that the future existence of the sun and earth in approximately their present states will extend over many hundreds of millions of years.

Sun Spots. The most conspicuous markings ever observed upon the sun are relatively dark spots which frequently appear in its luminous surface and last from a few days to a few months. The opaque, extremely luminous surface of the sun is called the *photosphere.* The sun spots are phenomena of the atmosphere. They are composed of a dark nucleus, called the *umbra,* which is surrounded by a somewhat lighter band, called the *penumbra.* The penumbra often is composed of a series of filaments reaching from the light photosphere into the umbra. The spots have been spoken of as being dark. This statement is slightly misleading, for they are only relatively dark with respect to the intensely luminous photosphere. The actual umbrae of the spots are as bright as the most intense artificial light we have.

The diameters of the spots may be anywhere from 500 to 50,000 miles, and some penumbrae reach up to 200,000 miles. Often a single penumbra may contain many umbrae in its interior. The development of a sun spot is usually preceded by indications of violent disturbance in its region, and bright points with intervening dark places are generally observed immediately before the appearance of a spot. The dark places unite and form a spot after an interval of a few hours or in some cases a few days.

The sun spots have the appearance of being dark holes in the surface of the sun. We unconsciously draw this conclusion because our experience on the earth tells us that holes into its interior, such as tunnels and the mouths of mines, appear dark. If our experience had been the opposite, then undoubtedly a dark spot on a distant world would appear as a mountain to us instead of a hole into its interior. Such a conclusion would be more nearly correct in the case of the sun spots. Instead of being dark openings into the interior of the sun they are masses of cooler gas which are usually

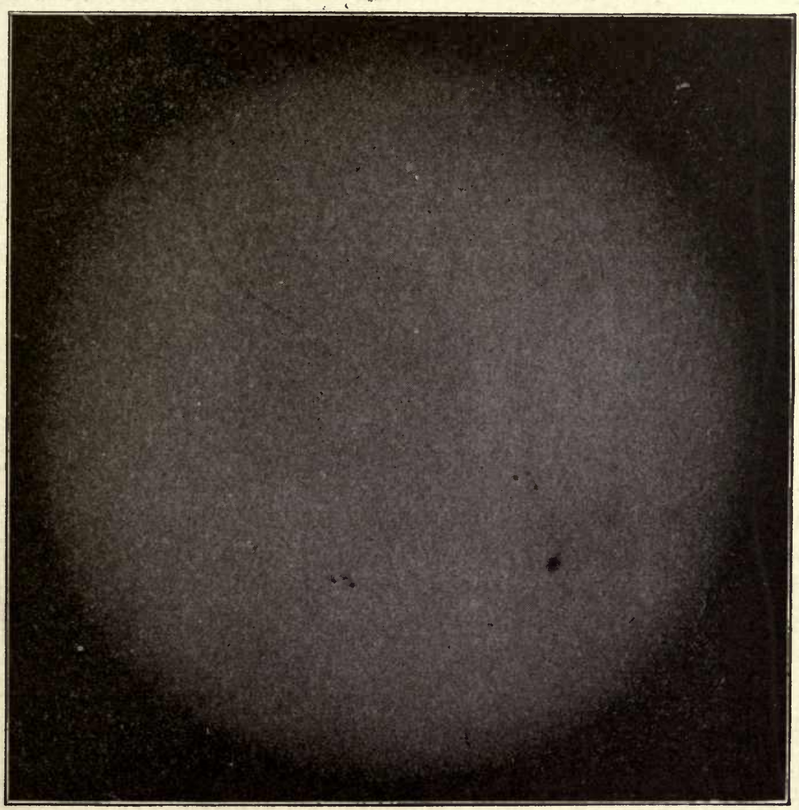


Fig. 92. Photograph of the Sun Showing Spots on Its Surface

above the general surface of the sun's photosphere. (See Fig. 92.) This is proved by the fact that as they appear near the margin of the sun they are relatively more conspicuous than they are at the center of its disk. Fig. 92 is a direct photograph of the whole disk of the sun showing several spots and the absorption near its margin.

The number of sun spots varies greatly from year to year and they are not uniformly distributed on the sun. They occur in greater numbers for a few years and then are less numerous, running through the cycle of changes in about 11 years. They appear in greatest numbers in belts on each side of the sun's equator. When they begin to become more numerous, they appear first in greatest numbers at latitudes about 35 degrees north and south of the equator. As time goes on they appear most frequently in lower and lower latitudes, reaching their greatest numbers when they are at about 20 degrees north and south of the equator. Then they begin to diminish in number and size and disappear at latitudes approximately 6 degrees north and south. At the same time a new series begins in the higher latitudes.

From the observations of sun spots it has been possible to determine the rate of rotation of the sun. Considered as a whole, its period of rotation is about 26 days, and its motion is in the same direction as that of the revolution of the planets around it. The sun does not rotate as a solid, but its equatorial zone moves faster than those parts in higher latitudes. The equator rotates in a period of about 25 days, spots in latitude 30 degrees complete their revolution in about 26½ days, and those in latitude 45 degrees in about 27 days. Spots are not seen in latitudes higher than 45 degrees. The rotation of the sun has been determined in several other ways, principally by observations of bright spots and great elevations which the spectroscope shows, and there is in a general way agreement of these results with those obtained by the observations of spots.

Different Layers of the Sun. The lowest layer in the sun which we can see is the photosphere, mentioned above. It is the opaque, apparently solid or liquid surface of the sun. Certainly, instead of being in a solid or liquid state, it is almost entirely gaseous because of the sun's high temperature. It is largely composed of the ordinary terrestrial elements in a gaseous state, and has the appearance of being a continuous surface because of the immense numbers of small liquid particles of carbon, rock material, and iron floating in it. It is somewhat analogous to clouds in our atmosphere. A cloud appears to be an opaque solid substance when seen at a distance, but as a matter of fact it is almost entirely gaseous. It gets its appearance from great numbers of minute particles of water floating in the atmosphere.

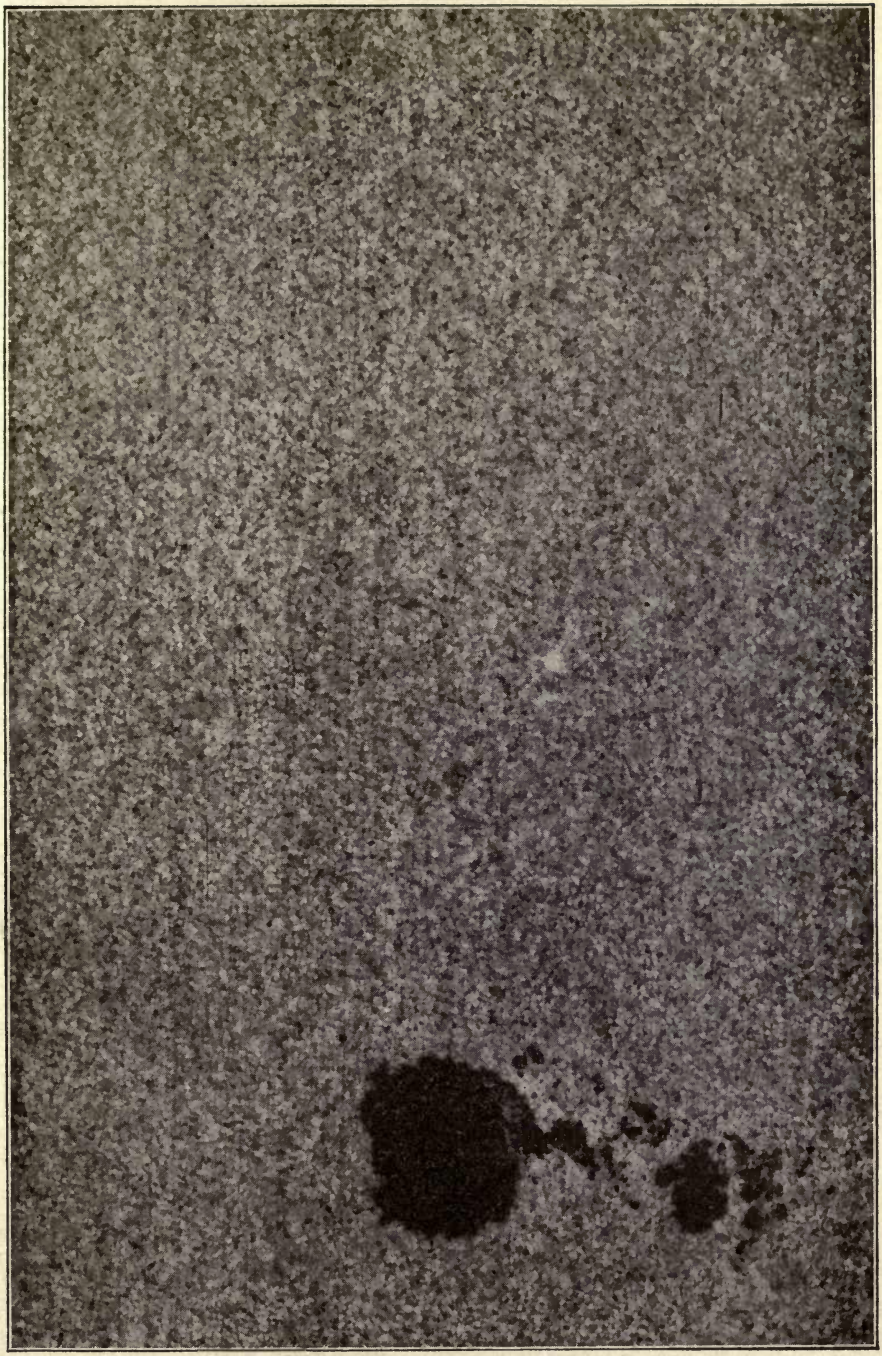


Fig. 93. The Sun's Photosphere Highly Magnified

In Fig. 93 is shown a small portion of the photosphere highly magnified. It is seen to be composed of a large number of minute granules with darker places between. The light spots are the tops of ascending currents which are bringing the heated material up from the interior to restore that lost by radiation; the darker places

Fig. 94. Eruptions from the Sun Photographed at the Yerkes Observatory by Fox

are where the partially cooled gases are sinking back into the depths. These bright spots are generally from 500 to 1,000 miles in diameter.

Above the photosphere lies a less intensely heated atmosphere, called the *reversing layer,* which contains at least about half of our terrestrial elements, all in the gaseous state. Among these elements are a large fraction of the metals with which we are familiar. The thickness of the reversing layer averages about 500 or 600 miles.

Mixed throughout it and possibly to some extent below it, is a thin cloud of small liquid or solid particles. The effect of this cloud is to absorb some of the light radiated by the photosphere and to reduce its intensity, particularly near the margin, as is shown in Fig. 92. Above the reversing layer is what is called the *chromosphere* (color sphere). This is a gaseous envelope of 5,000 to 10,000 miles in

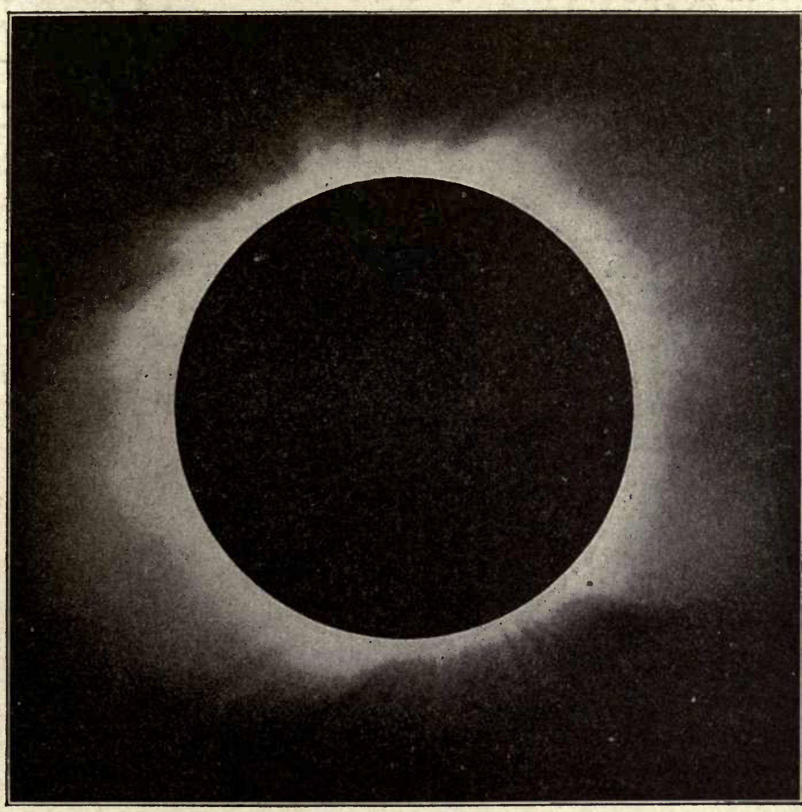


Fig. 95. The Sun's Corona Photographed at the Time of a Total Eclipse of the Sun in 1900

depth. At the time of total eclipse it can be seen as a scarlet ring surrounding the entire sun, whose surface seems to be seething with tongues of leaping flames. The spectroscope shows that the chromosphere is made up of luminous hydrogen, helium, and calcium.

The photosphere seems to be relatively quiet and continuous except where it is broken up by the spots. On the other hand, the chromosphere is the seat of numerous disturbances. Vast eruptions, called *prominences,* rise up from it to altitudes of from 50,000 to 300,000 miles with velocities sometimes as great as 500 miles per second. Fig. 94 is a photograph of some of these remarkable streams of material. On the sun explosions frequently take place in which masses of matter, whose volumes are greater than that of the earth, are thrown aloft to a distance farther than from the earth to the moon. This material, which rises in prominences, goes up and often turns over in long graceful streamers similar to the path of a sky-rocket, and plunges back again upon the sun.

Outside of the chromosphere is the *corona,* a vast envelope surrounding the sun and reaching out to 500,000 or 1,000,000 miles from it. The corona can be observed only at the time of total eclipse because it is so faint that the illumination of our atmosphere entirely obscures it. It has some of the properties of an atmosphere, and some which are considerably different. It does not uniformly surround the sun but stretches out farthest in the plane of its equator. Its shape varies from time to time with the period of the sun spot activities, and is undoubtedly associated with the disturbances on the sun's surface. Around the poles of the sun it is arranged in streaks, showing that strong magnetic forces are at play there.

Fig. 95 shows a photograph of the corona at the time of a total eclipse in 1900.

Spectrum Analysis. When substances are in the gaseous state and luminous, they give forth vibrations whose character depends upon their chemical constitution. The vibrations are distinguished from one another chiefly by their frequency, or the number given out per second. For example, incandescent hydrogen gives vibrations of a certain frequency, and incandescent oxygen gives vibrations of quite a different frequency, and so on for all the elements. The different light radiations from different elements are somewhat analogous to the different sound vibrations given forth by different kinds of bells, the pitch depending upon the number of sound waves given out per second. The reason that the matter must be in the gaseous state in order to get its characteristic spectrum, is that when it is in the solid or liquid state, the vibrations of the parts of the molecules which produce the light waves are interfered with by their being restrained by the neighboring molecules, and are therefore, not free to vibrate with their normal frequency. But when matter is in the gaseous state, as was explained in connection with the atmosphere, the molecules are independent of one another, except for brief times during collisions, and the normal oscillations take place unhampered. Consequently, the character of the vibrations of the molecules depends simply upon their structure. It is clear from this that if some means can be devised of discovering the character of the vibrations coming from a luminous gas, its nature can be determined in this fashion. The spectroscope is an instrument precisely for this purpose.

Fig. 96 shows the principles upon which spectrum analysis depends, though an instrument for practical use is modified so as

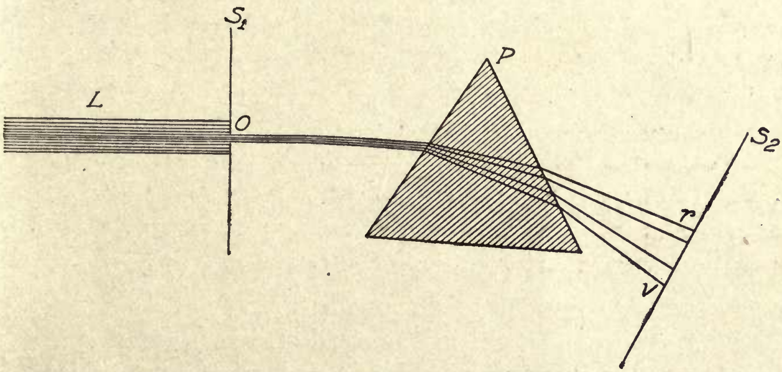


Fig. 96. Diagram Showing the Dispersion of Light Which Passes Through a Prism. Dispersion is at the Basis of Spectrum Analysis

to get a brighter spectrum. Let L be a dense beam of parallel rays of white light which fall on the screen S, at O. Suppose O is a narrow opening of the slit through S_1, which may be from $\frac{1}{100}$ to $\frac{1}{1000}$ of an inch wide. A thin slice of light passes through O and falls on the prism P. It strikes the first surface of P obliquely and its direction is bent as it enters it. The direction of the light is not only bent, but the light is spread out into its different colors. When the light emerges from P it is bent still farther and spread out still more. It may be caught upon the screen S_2, when it will be found that it consists of a band of colors varying from the violet v on the end which is bent the more, to the red r on the other end. The violet rays are the shortest (that is, the rays with the greatest frequency) which are visible to the human eye, and the red are the longest.

Beyond the violet there are the chemical rays and beyond the red in the other direction the heat rays.

Now, suppose a single substance in the gaseous state is heated to incandescence. For example, let us consider sodium, which is the metal constituent of ordinary salt. The light will appear to the eye as yellow and when it passes through the prism and falls on the screen S_2, there will be seen light at two places near together in the yellow. That is, sodium in the incandescent gaseous state gives forth vibrations of two different frequencies which are so near together that they both are yellow light. It is found by experiment in the laboratory that sodium always gives these two kinds of yellow light, and that no other substance gives exactly the same kinds of light. It must be understood that the actual instruments in use are much more powerful and give a much brighter spectrum than that indicated in the simple sketch of Fig. 96. Now, suppose iron is made incandescent and that it is in the gaseous state. When its light is passed through the prism P and falls on the screen S_2, it will be found that there are bright lines at very many places. The iron molecule seems to be extremely complex and gives forth many kinds of vibrations, but the important fact in this connection is that it always gives the same vibrations and it gives no vibrations which are emitted by any other substance whatever.

Now, suppose that the light instead of coming from a point in the laboratory comes from the distant sun, or even from the much more distant stars. The character of its vibrations will not have been changed in its journey through space any more than the character of the vibrations from a musical instrument will be changed by passing some distance through the air; the tune is the same whether the instrument is near to us or far from us. It follows that if the distant object is an incandescent gas its light will be analyzed into its separate parts and will fall on the screen S_2 at distant places, depending upon the constitution of the gas. If the substance is one with which we have become familiar in our laboratories we shall recognize its presence by the character of its light when analyzed. In fact, if the source of light is composed of a mixture of many substances the presence of all of them can be determined, for though originally it is a mixture of various colors the spectroscope will separate them into their constituent parts and each one will be distinct from every other. For example, if there were a mixture of sodium and iron the yellow lines of sodium would appear in the spectrum, and also the numerous lines of the iron. When the light is thus analyzed into its separate parts, the presence of one kind of lines does not interfere with the detection of any other kind. It is clear, therefore, from all of this discussion that the chemical constitution of an incandescent gas can be determined by means of the spectroscope, however far away it is in space. This remarkable process has been understood for about 50 years. Before its discovery it was supposed that while we can determine the motions of the heavenly bodies and in most cases their masses and dimensions, nevertheless, their constitution was a field forever closed to us.

There is another phase to spectrum analysis which in application is often more important than the preceding results. Suppose the light L is white; that is, that it comes from an incandescent solid or liquid. Then, as has just been explained, its spectrum will be continuous, and the substance of which it is composed can not be determined. But suppose that between S_1 and P there is interposed a cooler gas. This does not mean by any means that it shall be cold, but simply that it shall be less luminous than the source of the light L. This cooler gas will absorb some of the light L, and the important fact is that it absorbs precisely those vibrations which it would itself give out if it were incandescent. For example, suppose the cooler gas between S_1 and P is sodium. Then the spectrum on S_2, instead of being a continuous band of light from the violet to the red, will be a continuous band, except where it is crossed by two dark lines in the yellow at precisely the place where the yellow bands of sodium fall. That is, the interposed sodium gas has been transparent to all the colors except those which it itself radiates. This absorption by a gas of the same colors it radiates is analogous to the fact that a musical instrument, for example a piano, will take up those same vibrations when produced on another instrument that it is capable of giving forth. If middle C on one piano is struck and the key of middle C held down on a neighboring one, the second one will be set vibrating by the first, but if D be held down on the second one no sensible vibrations will be induced.

It follows from these principles that if the source of light is an incandescent solid, and if a cooler gas is between it and the observer,

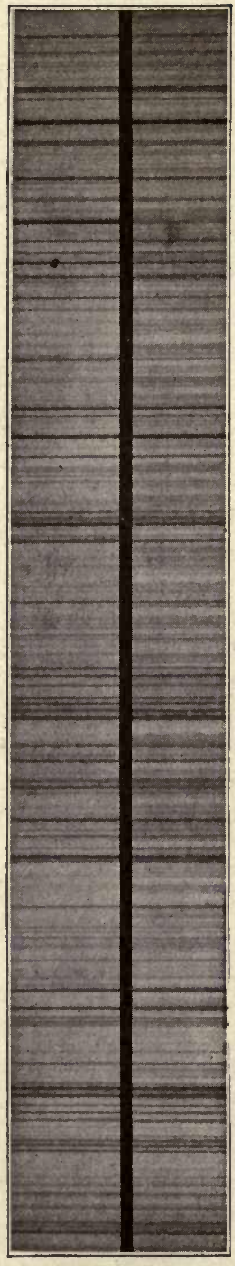


Fig. 97. A Portion of the Solar Spectrum on a Large Scale

he can determine the chemical constitution of the interposed cooler gas but not of the actual source of light. Let us apply these results to the sun. The photosphere is the main source of light in it and, as has been explained, the photosphere owes its intense luminosity and opaque appearance to the fact that it is made up of small drops of liquid particles of carbon, iron, rock material, etc. The light from this photosphere passes through the cooler gaseous envelope above it, called the reversing layer. The reversing layer subtracts from the light of the photosphere certain rays and produces many dark lines in the sun's spectrum, which would otherwise be continuous. Fig. 97 shows a small part of the solar spectrum; the left part is the spectrum of the photosphere and the right that of a spot. With the powerful modern instruments 20,000 lines can be observed in the spectrum of the sun. So far about 12,000 of these lines have been measured. While not all of them have been identified with terrestrial substances, about half of the elements known to the earth have been found to exist in the sun. Among the more common ones we may mention hydrogen, helium, carbon, oxygen, sodium, magnesium, aluminum, silicon, potassium, calcium, iron, nickel, copper, zinc, silver, tin, and lead. The state of the sun can be imagined when it is found that in its cooler atmosphere all of these elements are in a gaseous condition.

Another very interesting application of the spectroscope has been made in the photography of the sun. In the case of certain lines, the vapors which surround the photosphere are so extensive and so dense that they cut out nearly all the light which comes from it, but above these vapors there are floating luminous clouds of the same material. The width of an absorption line increases with the density of the absorbing medium. In the case under consideration the lines are wide because of the density of the absorbing gases which are subject to great pressure. The higher luminous gases are subject to less pressure and give, therefore, a bright line in the center of the dark absorption line. That is, in the sun's spectrum in the case of some wide heavy lines there are bright centers. The light in these centers comes from definite elements. When the sun's light is

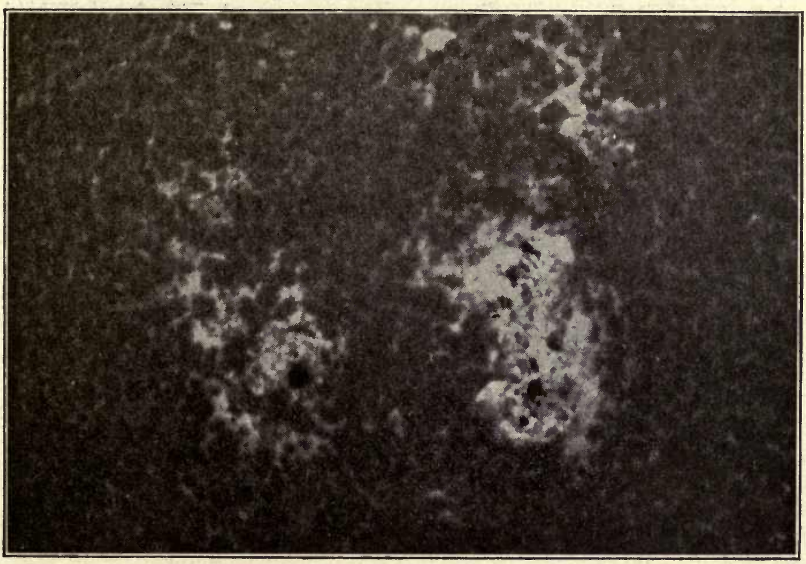


Fig. 98. Photographs of Spots Taken with Calcium Light

spread out into a spectrum so that the light from each incandescent substance comes out in a different place, it may all be screened off except that which comes from a single substance, If a photograph is taken, a picture of the sun is obtained with the light which comes from a single element. In order to obtain a photograph of the whole sun it is necessary to have the apparatus adjusted so that the photographic plate will move at the same time the spectroscope is pointed at different parts of the sun, for otherwise the images of different parts would fall upon the same part of the photographic plate, and we should obtain a composite picture rather than a picture of its whole surface. When the instrument is properly adjusted, a photograph of the whole sun in light from one element is obtained, and the picture shows distribution of this element in the sun at the time in question. This instrument is called the *spectroheliograph.*

Figs. 98 and 99 are spectroheliograms of the sun. Fig. 98 shows a small portion of the solar disk including some spots as photographed with calcium light, and Fig. 99 shows the same region as photographed with hydrogen light. The luminous places are where the element in question was abundant in an incandescent

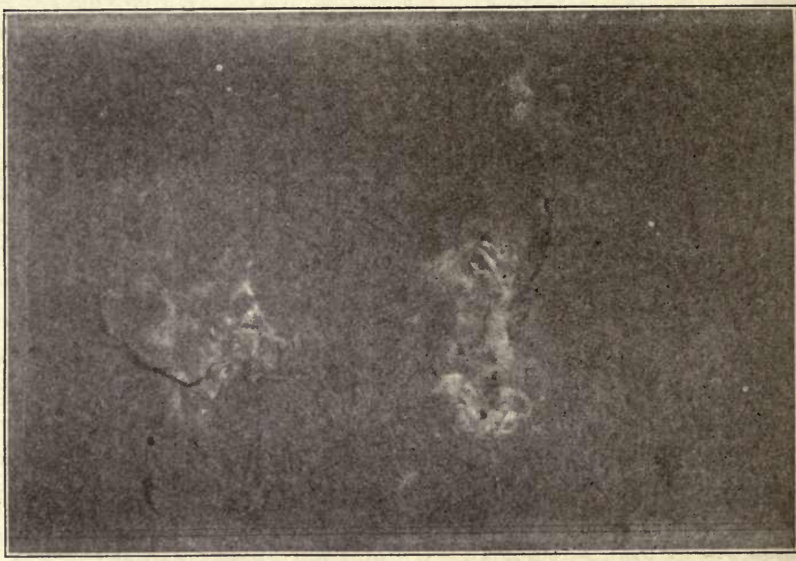


Fig. 99. Photograph of the Same Spots as Shown in Fig. 98 Taken with Hydrogen Light

state. The relatively dark places are where the element was present, but in such a cool condition that it absorbed almost completely the light from the photosphere.

THE SIDEREAL SYSTEM

Distribution of Stars. In connection with the work on constellations we saw that stars were apparently grouped in various parts of the sky. This apparent aggregation here and there depends, of course, upon our position with respect to them. At present we are not interested in their apparent grouping, but in their actual distribution in space. This is, of course, related somewhat to their apparent distribution; or, at least, their apparent distribution depends partly upon their actual distribution.

An examination, either without a telescope or with a telescope, shows that the stars are much more numerous in the direction of the Milky Way than they are in directions at right angles to it. If a given area be counted in the plane of the Milky Way and an equal area be counted at right angles from it, it will be found, especially if very faint stars are included, that the region in the Milky Way has many times more stars than the other one. It follows that stars are either more closely crowded together in the direction of the Milky Way, or that in those directions we are looking through a greater depth of them. That is, appearances have led to the conclusion that the system of the stars is a great disk or grindstone-shaped figure in space. The sun and its family of planets is somewhere in the interior of this vast aggregation of stars. The plane of the disk is the plane of the Milky Way. When we look out in the direction of the Milky Way we see a vast aggregation of stars because we are looking through a greater depth of them; and when we look out at right angles to it we see fewer stars because we are looking in a direction where we sooner reach the borders of the system.

The fact that photographs of the Milky Way show dark rifts and breaks, as in Fig. 37, is against this theory without some considerable modifications. Recent studies of the apparent motions of the stars show that those so far examined, which, of course, do not include the great majority of those stars which are extremely faint, belong, on the whole, to two great star streams. Probably the sidereal system is made up of a relatively small number of great star families, the numbers of which move in parallel lines with approximately the same speed.

Most of the stars are so remote from us that their distances can not be found by direct processes. One of the proofs of the earth's revolution around the sun is the parallax that certain stars are observed to have. (See Fig. 20.) But parallaxes of a sufficient number of stars can not be obtained by this method to give any general idea of their distances when considered as a whole. There are, however, certain indirect processes which have led to most interesting results. If the stars were still and the sun in motion, they would apparently drift back in the direction opposite to that of the motion of the sun. The apparent rate at which they would drift back would depend upon their distance from the sun. It is analogous to what one observes when he passes through the country on a train; the objects which are near apparently go back at a high speed, while those which are far away seem to move very slowly. Now, in the case of the stars, if the rate at which they apparently go back were observed, their distances could be computed. If their motions in the backward direction were not enough so they could be observed in one year, then perhaps they could be observed in 10 years, or 100 years. In this way the distances of all the stars which are not in the direction in which the sun is going, or in that from which it has come, could be determined.

Unfortunately for the application of this method the stars are not at rest. The spectroscope and a study of their apparent motions show that on the whole they are moving at the rate of several hundred millions of miles per year. It follows that the distance of any one star can not be determined from its apparent backward drift because this depends not only upon the motion of the sun but also upon its own motion. But taking the stars as a whole their distances can be determined in this fashion. On the whole, they will not be moving in one direction more than another, and it is possible, therefore, by an averaging process for any group of stars, say of a definite magnitude, to find their average distance from the sun.

The stars belong to two main types, depending upon the kind of light they send to us as determined by the spectroscope. The stars of Type I are those which are blue, or bluish white, and are supposed to be in an early stage of their evolution. The stars of Type II are yellow and similar to the sun. It is found that the stars of Type I of a given magnitude are on the average considerably farther from us than those of Type II.

A statistical study shows that on the average first magnitude stars of Type I are so far away that it takes their light about one hundred years to come to the earth, while light from first magnitude stars of Type II comes to us in about 43 years. The formulas on which the computations are made are based upon stars of the first nine or ten magnitudes. They are probably not very exact for the brighter stars, because there are too few of them to make the statistical method very safe; and they are probably inexact for the very faint stars, because they have not been used in deriving the formulas. But applying the formulas it is found that on the average the light of the ninth magnitude stars of Type I is more than 700 years coming to us, and of Type II a little more than 300 years. From the same formulas it is found that the light of stars of the fifteenth magnitude of Type I reaches us more than 3,000 years after it leaves the stars which radiated it, and of Type II, more than 1400 years.

In getting these results it has been necessary not only to observe the apparent motions of the stars but to know the rate at which the sun is moving relatively to them. The motion of the sun is determined by means of the spectroscope. The velocities of many stars relative to the sun are found, and by an averaging process it can be determined from these data in what direction the sun moves and with what speed. Thus we have the remarkable result that the spectroscope, which can not be used in measuring distances directly, is indirectly used in determining the distances of stars so remote that the ordinary means entirely fail. It is characteristic of science that various methods are woven together to secure its results.

In order to determine the magnitude of the sun relatively to other stars we can compute how bright it would be if it were at the distance of the average first-magnitude stars of either Type I or Type II. The direct measurements of the light received from the sun show that its magnitude is about -26.4, and it follows that if it were at the average distance of the first-magnitude stars of Type I it would be only a little brighter than an eighth-magnitude star, or $\frac{1}{60}$ as bright as an average star of Type I. If it were at the average distance of the first-magnitude stars of Type II it would be of the sixth magnitude, or about $\frac{1}{10}$ as bright as the average star of Type II. It is thus apparent that our sun is considerably below the average of other suns in magnitude.

Groups of Stars. The results given in the preceding section refer to stars as a whole and do not take into account their groupings. Just as the sky is seen to contain groups of stars, so the measurements of their positions with the telescope show that in many places in space large numbers are grouped in relatively small volumes. Among the best-known groups are the Pleiades, Fig. 41, the Hyades, Fig. 35, the Coma Berenices, Praecepe, Cancer, and Orion. While they differ greatly among themselves, a general idea of their enor-

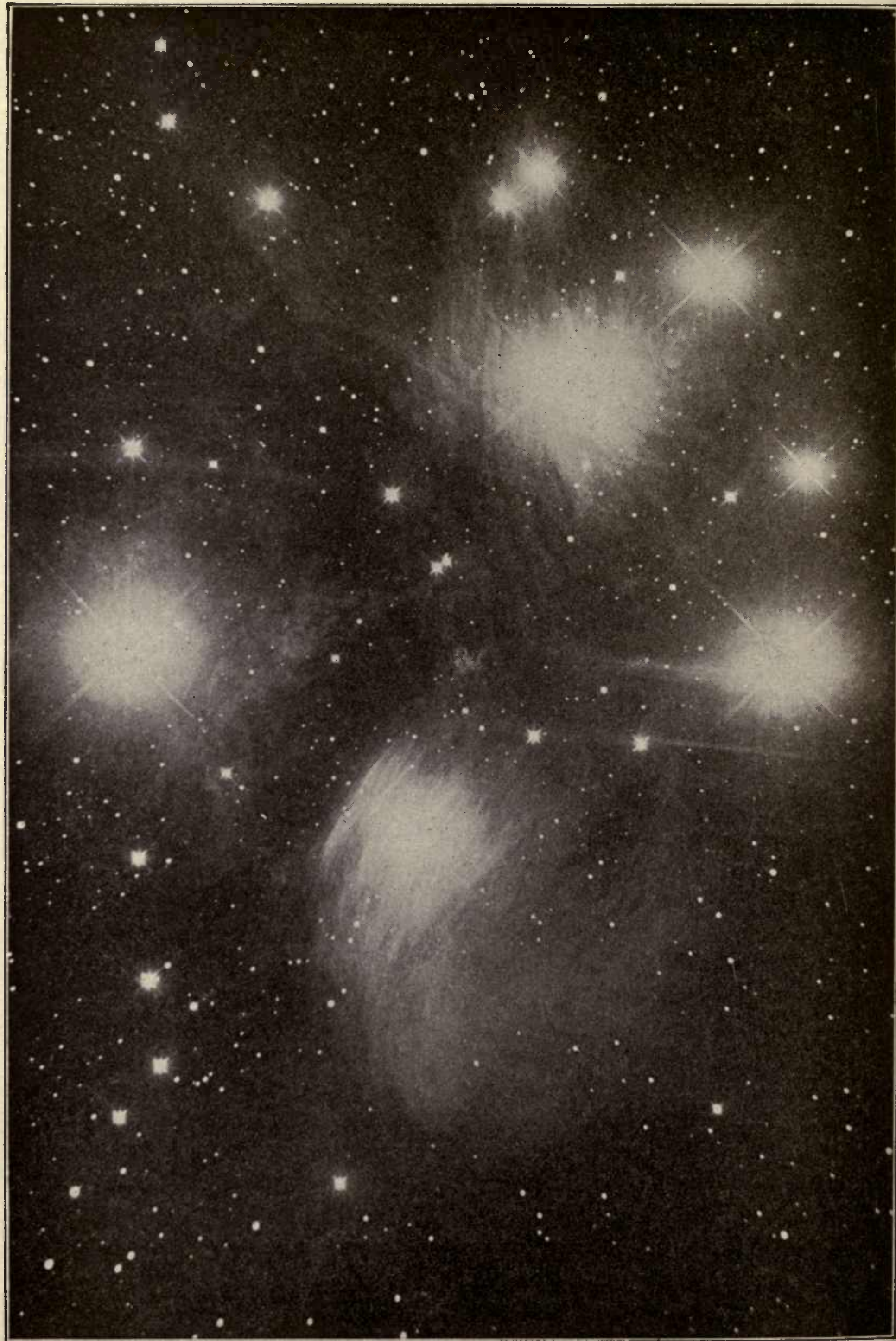


Fig. 100. Photograph of the Pleiades Showing the Nebulous Material Which Surrounds the Principal Stars

mous dimensions and splendid character can be obtained from a description of the Pleiades. The seven brightest stars of the Pleiades cover nearly three square degrees of the sky and, as was stated in the discussion of the constellation Taurus, they are so far away that it takes their light nearly 300 years to come to us. At this distance the sun would appear as an insignificant ninth-magnitude star. The Pleiades average more than one hundred times as great as the sun in light-giving power. The distances between the stars of this group are such that it requires several years for light to pass from one to the other. Besides the seven stars which are visible to the unaided eye, the telescope shows 45 others which have the same motion in both direction and speed and whose spectra are similar. They are undoubtedly a part of the same great family of stars. In addition to these stars there are about 2,000 fainter ones, which so far have not been examined with sufficient care to enable us to determine whether they are really members of the same group or not.

With the most powerful instruments and under good conditions some of the stars of the Pleiades are seen to be surrounded by very faint nebulous masses. When photographed with reflecting telescopes, which are peculiarly suited for bringing out the details of very faint and diffuse objects, the principal stars of the Pleiades are seen to be entirely surrounded by enormous masses of nebulous matter reaching almost from star to star. Fig. 100 is a photograph of this region taken at the Yerkes Observatory. The magnificence of a great group of stars averaging more than one hundred times the splendor of our sun, and of such dimensions that it takes light years to travel from one to another, and all enshrouded in huge masses of nebulous material is enough to stagger the imagination. Surely these stars in a very real sense form a family and have had a common origin.

Long exposure photographs of the Pleiades' region covering the neighboring sky show that surrounding them there are very faint nebulosities which cover a region more than 10 degrees square. These nebulous masses are incomparably greater in extent than those which are shown in Fig. 100.

In addition to the scattered groups of stars, such as the Pleiades, there are other groups which are in some respects more wonderful. They cover very small portions of the sky, generally much less than the apparent size of the moon, and contain in these small areas from 3,000 to 60,000 stars. There are more than 100 of these systems known, and they are found in all parts of the sky, especially in or near the Milky Way. Fig. 101 shows one of these magnificent star clusters which is situated in the constellation Hercules. The stars in these clusters are not only individually invisible without a telescope, but taken all together they can not be seen without optical aid.

Fig. 101. The Great Star Cluster in Hercules

They are generally very faint, ranging from the twelfth to the sixteenth magnitude. It is a question of the highest interest whether these systems are made up of great suns like our own, which appear feeble and near together only because of their enormous distances from us, or whether they are small suns closely crowded together and of not very great distance from us. If the latter hypothesis is correct they have had a peculiar evolution quite different from that of the great mass of stars. It has not been possible so far to measure directly the distance of any globular cluster. We can make only an inference of their remoteness in the sky from their relative fixity on the celestial sphere. Thus far observations have not shown any direct motions of any of the star clusters. In one or two cases observations have shown the motions of an individual star in them, but it seems probable at present that these stars are only apparently in the clusters. It must be remembered that since stars cover rather thickly nearly the whole sky, there will be some in the direction of the clusters, and apparently in them, which do not actually belong to them. If such a star were much nearer to us than the cluster a moderate motion would give it the appearance of moving rapidly in the cluster.

To summarize, the facts are that no cluster as a whole has been observed to have any motion on the celestial sphere, and only a very few individuals of certain clusters have been found to have motions in the clusters themselves. We infer from their fixed positions on the sky that they are actually very remote from us. Of course, time will reveal their actual motions and permit us to make more than a conjecture. At the present time it seems very probable that they are distant at least 400 light years. At any rate, we may make the assumption in order to obtain some sort of a mental picture of what a cluster really is. At that distance our sun would appear as an eleventh-magnitude star. If the assumption is correct, it follows that the stars of the clusters are somewhat fainter than our sun though comparable to it. The more interesting question is how far they are from one another. A computation shows that in the star cluster whose photograph is given in Fig. 101, where in its center the stars seem to touch one another and where there seems to be imminent danger of collision, the distance of one star from another is on the average 30,000 times as far as the distance from the sun to the earth; or, in round numbers, the distance from one star to another in Fig. 101 is 30,000 times 100,000,000 miles. Since gravitation varies inversely as the square of the distance, it is not surprising that the interactions of these stars on one another do not produce sufficient motions to be observed in the short time they have been followed by our great telescopes. In these clusters there is abundant room for almost permanent motion of the stars without any danger of collisions, and each sun might be accompanied by a retinue of planets without their being in any particular danger of destruction from other suns.

A remarkable peculiarity of the stars of some of the clusters is that a considerable fraction of them vary in the light they radiate. The period of variation is almost the same for the variable stars of one cluster but may be somewhat different for those of another. The periods are generally about a day. The light from the stars is sensibly uniform except for a short time when it flashes out with from two to six times its ordinary brilliance. More than 500 of this type of variables have so far been found. There is no explanation for this most peculiar variability.

Recent measurements of the distances and motions of the stars show that our own sun is a member of a rather open cluster of perhaps about 100 stars. Our great distance from all other suns gives us an idea of the distances separating the stars in the clusters.

Double Stars. A few double stars have been known since the invention of the telescope. They are two suns which are so near together that they appear as a single one without an instrument. In modern times the limits are still closer than this definition would lead one to infer, for a star is not considered as being a real double unless the distance separating its components is less than 0.1 of that which is the limit of visibility without telescopic aid. There are very many of these objects known at the present time, and in Burnham's great catalogue of double stars the observations and descriptions of about 13,000 are given.

Originally it was supposed that our sun and planetary system is a type of all the systems in space, and consequently that double stars are simply examples of two suns happening to be in the same direction in space. A computation shows easily that the probabilities are against very many pairs existing in which two are seen almost exactly in the same direction and are not actually associated. About 120 years ago Sir William Herschel began systematic observations of the double stars in order to determine their distances; for it was clear that if they were only apparently in the same direction, and one many times as far away as the other, the near one would apparently move with respect to the remote one while the earth was making its revolution around the sun. Herschel did not find what he was looking for, but was surprised to observe after a few years that in some cases the two stars were going around their common center of gravity. This established the existence of systems of two suns revolving near each other, and furnished a model quite different from that of a single sun attended by a family of planets.

The discoveries which Herschel's successors have made with modern telescopes have shown that these double-star systems are very numerous, and the number known is constantly being added to by the observations which are carried on at all the leading observatories. Those stars which form an actual physical system are

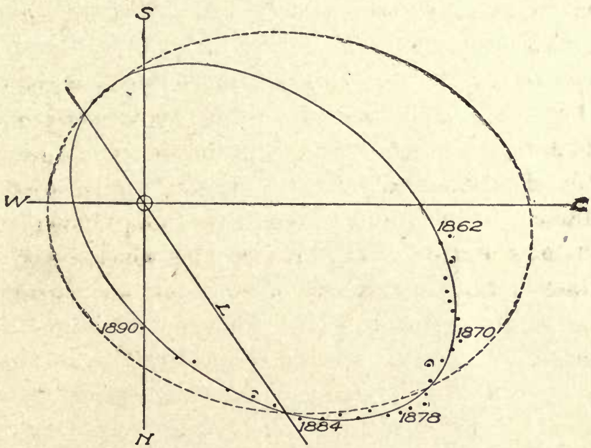


Fig. 102. The Full Curve is the Apparent Orbit of the Companion of Sirius; the Dotted Curve Its Actual Orbit

called *binaries*. The periods of the binaries range from about five years to hundreds, and perhaps thousands, of years. The orbits of those whose periods are very long are, of course, not well known because of the short time covered by the observations. The stars whose periods are short are near one another, and the stars whose periods are long are on the whole very remote from one another. Fig. 102 shows in a dotted curve the real orbit of the companion of Sirius with respect to the principal star, which is represented by a small circle where the axes cross. The plane of the orbit is tipped through an angle of about 45° around the line *L*. Consequently, instead of seeing the companion move along the dotted ellipse, we find it moving along the full line ellipse, which is the projection of the other.

TABLE VIII

Binary Stars Whose Masses and Distances Are Known

Star	Semi-axis	Period	Mass	Light	Eccentricity
Alpha Centauri	23.6	81	2.0	1.7	0.53
Sirius	21.7	52	3.7	32.0	0.62
Procyon	10.0	40	0.6	8.5	
Eta Cassiopeiae	41.0	196	1.8	1.0	0.51
70 Ophiuchi	24.0	88	1.8	0.7	0.50
85 Pegasi	19.5	24	11.3	2.2	0.59

The apparent distances of double stars from each other are determined by direct observations with the telescope. Their actual distances from each other can not be found unless their distances from the earth are known. In a few cases the distances of binary stars are known, and in these cases the real distances of the two members from each other can be determined. When the distances of two stars from each other and their periods of revolution are known, their masses can be found just as the mass of the planet can be found from the period of a satellite which revolves around it at a known distance and in a known period. Also, when the distances of the stars are known, their luminosity compared to that of the sun can be determined.

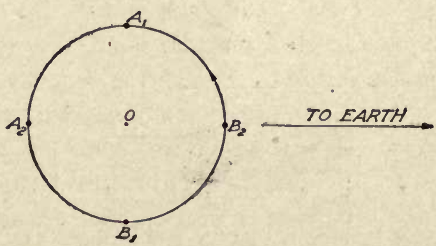


Fig. 103. The Shift in the Spectral Lines of a Binary Star

There is one striking difference between the orbits of binary stars and the orbits of the planets in their motions around the sun. While the planetary orbits are nearly round, the orbits of the binary stars are, on the whole, very elongated. The average eccentricity of those which are best known is in the neighborhood of 0.5. Table VIII gives the stars whose distances, actual orbits, masses, and light in terms of the sun's light are known. In column one is the name of the star; in column two, the semi-axis of its orbit expressed in terms of the mean distance from the earth to the sun; in column three, the period expressed in years; in column four, the mass expressed in terms of the sun's mass; in column five, the light expressed in terms of the light radiated by the sun; and in column six, the eccentricity of the orbit.

Spectroscopic Binary Stars. In many cases there are two stars which are so remote and so close together that they appear as one when seen through the most powerful telescopes. The spectroscope has enabled us under certain circumstances to determine, nevertheless, their binary character. If a star is coming toward us, the lines in its spectrum are shifted toward the violet end, just as when a locomotive is approaching us the pitch of its whistle is raised. The approach of a star crowds the waves closer together and changes the color toward the blue end of the spectrum. Our eyes are not sufficiently sensitive to slight differences in color to enable us to detect this change, but it is possible in many cases to measure the shift in the spectral lines. A star receding has its lines shifted correspondingly toward the red end of the spectrum.

Suppose the circle in Fig. 103 represents the orbits of two equal stars revolving around their center of gravity O in the direction indicated by the arrow on the orbit. Suppose the earth is extremely far away in the direction indicated, and that the two stars appear single as seen through even the most powerful telescopes. Suppose also that they are chemically and physically the same, so that they have like spectra. Consider the system when one star is at A_1 and the other at B_1. In this position the star at A_1 is receding from the earth and the star at B_1 is approaching toward it at an equal rate. Therefore, the spectrum of the star A_1 will be shifted toward the red, and the spectrum of the star B_1 correspondingly toward the violet. The spectrum then will be composed of double lines whose distance apart will depend upon the relative velocities of the stars. For the velocities which are actually found the lines are always very close together.

Now, consider the system again when A_1 has moved forward to A_2 and B_1 to B_2. In this position the stars are neither approaching nor receding and their lines all appear single. When A_1 and B_1 have changed places the lines again appear double. The period of revolution is the time between the one doubling of the lines to the second following doubling.

In this way the existence of binary stars is not only proved, but it is possible to find out more about the orbits than is generally the case in ordinary visual binaries. The spectroscope shows not only the periods, but the velocities, of the stars in their orbits, from which we can compute their actual dimensions. Knowing the dimensions of the orbits and the periods, the masses can be found. The spectroscopic observations do not enable us to determine the distances of the stars from us and, therefore, we cannot determine their brightness.

Besides the spectroscopic binaries of the type just described, there are many others in which one of the two stars is so faint that its spectrum can not be observed. In such cases the star whose spectrum is visible shifts alternately toward the violet and the red ends of the spectrum. The period of the shift shows the period of revolution of the pair, and the amount of shift shows the dimensions of the orbit of the brighter star. It is not possible in this case to determine the exact masses because this determination depends upon the distance of the stars from each other, and this can not be determined from the distance of one alone from its center of gravity. A sort of lower limit to the masses can be found because the distances of the stars from each other must be greater than that of the more luminous one from its center of gravity, and in general will be more than twice that great.

There is another uncertain factor in the determination of these orbits, viz, the angle which the plane of the orbits makes with a line joining the stars with the earth. In the diagram and in the discussion so far it has been assumed that the plane of their orbit passes through the earth. It is obvious that in general it will be inclined to the line from the stars to the earth. Consequently, instead of having the total velocity of the stars in the case of the double lines, we shall have only that component which is toward the earth. This leads us in general to a too small value for the combined masses of the system.

The study of binary stars by means of the spectroscope was begun in 1889 and most of the work in it has been done since 1900. In 1905 there were 136 spectroscopic binaries known, and on January 21, 1910, there were 306. The number of orbits of those which are fairly well determined is now about 70. The periods range from less than five hours up to nearly two years. The distances apart of the components vary from 50,000 miles as a lower limit to nearly

105,000,000 miles. The eccentricities vary from practically zero to about 0.9. On the whole the stars with the shorter periods have the smaller eccentricities.

Variable Stars. The variability in the light of certain stars in the globular clusters was mentioned above. There are many other stars whose light varies in different ways. The first one known was Omicron Ceti, discovered in 1596. The next one was Algol (the Demon), discovered in 1783. Variable stars were not known in any considerable numbers until near the close of the nineteenth century, and now more than three hundred of these objects are in the catalogues.

In one type of variables the light of a star remains constant except for short intervals when it diminishes greatly in brightness. The typical star of this type is Algol, and there are about twenty-five such stars known. Their periods are generally less than five days. The explanation of their variability is that they consist of two stars, one of which is relatively dark, revolving around their center of gravity in a plane passing through the earth. The bright star shines with its customary brightness except when the dark star passes between the luminous one and the earth, and then its light greatly diminishes. It is obvious that these systems are in most respects analogous to the spectroscopic binaries and, indeed, in most if not in all cases the lines of the brighter component shift in a way which proves their binary character. The star Algol has a period of two days, 28 hours, 48 minutes, and 55 seconds. It is normally a star of the second magnitude, but at the time of eclipse it loses five-sixths of its light. This is a spectroscopic binary and the orbit of the brighter component is consequently known. Its distance from the center of gravity of the system is about 1,000,000 miles. From the duration of the eclipse and the rate at which the light fades and returns, it is possible to compute the diameters of the bright and faint stars. In the case of this star the bright component has a diameter of approximately 1,000,000 miles and the dark component 800,000 miles. From measurements of the distance of this pair, which unfortunately are subject to some error, it is found that the bright component radiates 80 times as much light as our sun. Taking into account the area of its surface, it follows that it radiates 52 times as much light per unit area as the sun does.

There are several slight variations from the type exemplified by Algol. One is that in which the stars are of unequal size but both bright. Then each eclipses the other in turn during their revolution. The star Beta Lyrae is an example of another type closely related to the Algol variables. The chief differences are that the light varies continuously from its maximum to its minimum and back to its maximum again. There are generally two minima and a single maximum. The explanation of these stars is that the two components revolve very near together and in a plane passing through the earth. Under these circumstances as soon as the first star passes out of its eclipse by the second, it immediately begins to eclipse the second. One minimum is when the fainter is between the earth and the brighter, and the other minimum is when the brighter is between the earth and the fainter. Of course, if the two were equal in all respects there would be a single minimum. The maximum is when the line joining the stars is at right angles to the line joining them with the earth, at which time the earth receives the full light of both of them. These stars have been found from the variation of light and the shifts of their spectral lines to be of enormous dimensions and very tenuous.

There is another type of variable stars of which Omicron Ceti is the best-known example. This star has been observed through more than 300 of its cycles. The periods of these stars are long and irregular. The time for minimum to maximum is generally considerably shorter than from maximum to minimum. The maxima and minima are subject to great irregularities, and there is no discoverable relation of them to the period. According to the observations of Sir William Herschel the star Omicron Ceti changed its light more than 10,000 fold in only four years. The spectroscope showed marked changes in the spectra of these stars, but no evidence of their being spectroscopic binaries. They are generally red stars which seem far advanced in their cooling, but we can imagine no internal disturbances which would cause the enormous fluctuations in their radiating power that is often observed.

There are besides the stars of the Omicron Ceti type others whose variations give no hint of periodicity. Some are characterized by their light suddenly flashing out with great brilliance, usually after intervals of many years of quiescence, and others unaccountably fade away and become invisible even through the most powerful telescopes. These stars are also generally red and sometimes apparently associated with faint nebulous masses.

Temporary Stars. Occasionally stars have been observed to blaze forth suddenly in parts of the sky (so far always in the Milky Way) where none had previously been seen, and then to sink away quickly into obscurity. They are characterized by a very sudden rise to a great maximum which in spite of later possible increases is never repeated. One of the most remarkable of these was observed in Cassiopeia in 1572, and was mentioned in the discussion of this constellation.

One of the recent remarkable stars of this type appeared in 1901 in the constellation Perseus. On February 19 of that year a photograph of the region where it later appeared was taken and did not show it. By the 23d it was brighter than the star Capella. In this short interval its light had increased more than 20,000 fold. A day later it had lost one-third of its light, and it steadily decreased in brightness until about the 22d of March, when it flashed up. It then diminished again until the 24th of April, when it had gone down to the sixth magnitude. At this time it flashed up again nearly to the third magnitude, after which it faded away and became entirely invisible by the end of the year.

The explanation of these temporary stars is that they are dark suns moving swiftly through space and that they suddenly encounter invisible dust clouds or nebulous material. Striking these tenuous masses with high speed, their surfaces are suddenly made to glow with a brilliant light analogous to that of the tiny meteors when they dash into our atmosphere. Since the surface only is heated the light speedily fails when the star passes through the material with which it collides. Secondary collisions with dark masses of the dust clouds or nebulous material cause the secondary flashes that sometimes are observed in these stars. The star Nova Persei was photographed a few months after it blazed forth and was found to be surrounded by a very faint nebulous mass. The explanation is that the nebulous matter which had previously been dark and invisible, became visible as it was lighted up by the glowing star. The star Nova Persei was so far from us that it took its light approximately 300 years to reach us. This means that the collision, instead

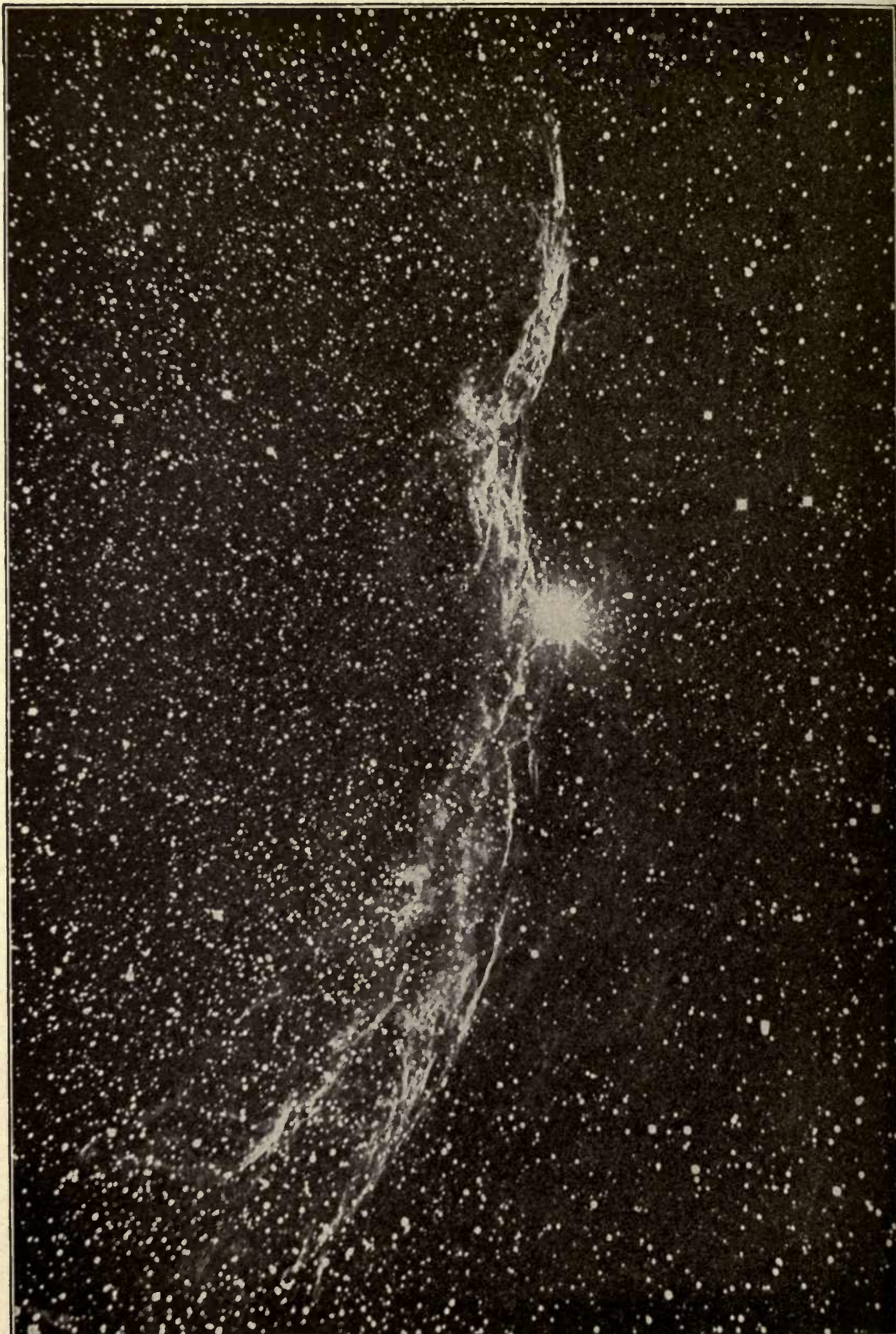


Fig. 104. Primitive Nebulous Material in Cygnus. Photographed at the Yerkes Observatory

of taking place in 1901 when the star was observed, actually took place about the year 1600.

Nebulas. Scattered here and there throughout space are great cloud masses of low luminosity known as nebulas. They are supposed to be the primitive world stuff out of which suns are made in very early stages of their development. Fig. 104 is a photo-

Fig. 105. The Trifid Nebula

graph of an extremely widespread, gauze-like, nebulous mass which is so faint that it is visible only in a very large telescope. This is about the most primitive type of world stuff with which we are acquainted. It suggests that the process of creation, or of evolution of matter from something more primitive, was not an event which took place at any one time and then stopped, but rather one which always has been and always will be taking place. That is, these photographs suggest that creation is a process continuously going on rather than one confined to any particular time. If this idea is correct the nebula whose photograph is shown in Fig. 104, is matter recently created, using *recently* in the astronomical sense.

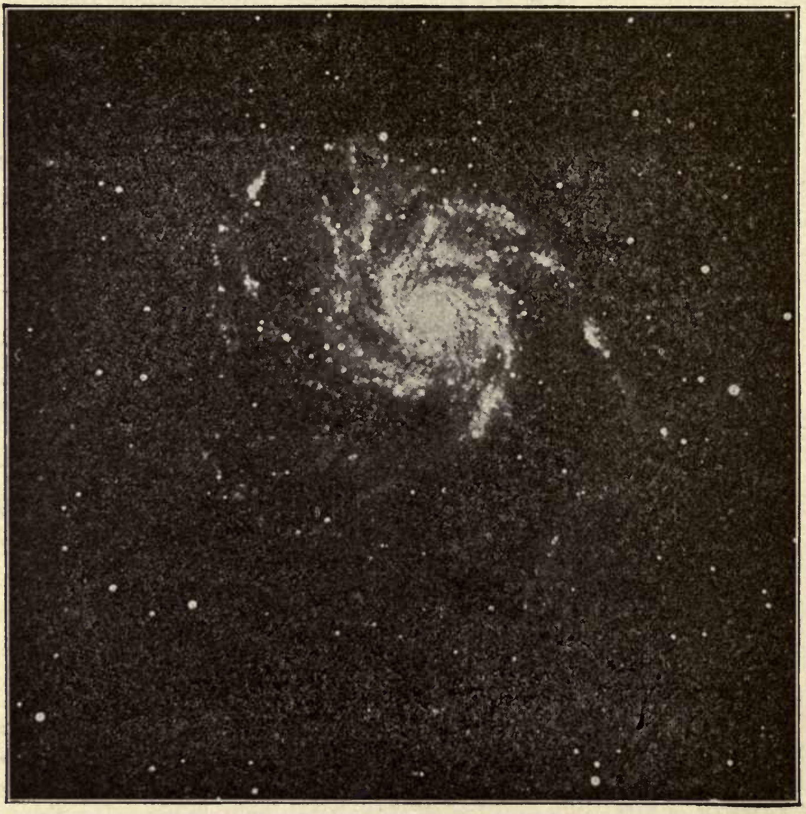


Fig. 106. A Spiral Nebula in Ursa Major

There are other nebulas which show a considerably higher degree of organization of matter as, for example, that in Orion, Fig. 43. There are others still farther advanced, as shown in Fig. 105. In addition to these more or less irregular nebulous masses, there are the spirals which exhibit a high degree of organization and to which we shall have occasion to refer in discussing the origin and evolution of the solar system. Fig. 106 shows one of these spiral nebulas which is in the constellation Ursa Major. There are still others associated with stars; and some, called "planetary nebulas," have the general appearance of a planet.

All the nebulas except the spirals have bright-line spectra instead of dark-line spectra like those of the sun and stars. This shows, in accordance with the principles of spectrum analysis, that the nebulas are masses of incandescent gas rather than luminous solids or liquids shining through cooler gases. Before these results were obtained by the spectroscope it was supposed that perhaps the nebulas were other galaxies of stars so far away that their individual members were not separately visible. The spectroscope, however, proves they are gaseous and this conclusion is in harmony with other considerations regarding the evolution of suns.

COSMOGONY, OR THE EVOLUTION OF WORLDS

Evolution. A slow change in one direction, especially if it be from the simple and unorganized to the complex and organized, is said to be an *evolution.* The central idea of it is that the change from one state to another is an orderly and continuous one rather than a chaotic and abrupt one. When considered in this way it is seen that evolution is simply a statement that the organization of the universe which makes science possible is extensive in time as well as in space.

In order to discover the evolution of any part of the physical universe it is necessary to know the condition of it at a given instant and the laws according to which it changes. For example, in order to determine the evolution of the solar system we must know its condition at one time and how its various members change. In the preceding pages a description of the solar system has been given and a synopsis of the chief laws which it obeys. If all of the data and all of the laws of change were known, and if one possessed sufficiently powerful mathematical processes for making the solution, then it would be possible to predict the condition of the solar system for indefinite time in the future, and to find what it had been for indefinite time in the past. Unfortunately, we are never able to determine fully all the factors which are involved in a series of changes, and it is equally certain that we do not know with absolute exactness all of the laws to which the system is subject.

For example, the temperature of a given place on the earth depends upon the temperature and the distance of the sun, the way the distance from the earth to the sun changes, the period of the earth's rotation, and many other factors. A great many of the determining factors are known exactly, or at least with a high degree of precision, but some are totally unknown. If the most important of them are known with a considerable degree of accuracy, predictions can be made with corresponding accuracy even though some of them remain unknown. Thus, in the case of the temperature of the place just mentioned, while many factors are unknown, predictions which are on the whole reliable can be made on the basis of those which are known. For ages to come the succession of seasons and of day and night at any one place can be accurately described. But it is not possible to predict the precise temperature changes even for a short time. Thus, we see that while it is possible to work out a general idea of the nature of the temperature changes, it is not possible, because of the imperfections of our knowledge, to describe them with absolute precision. The degree of accuracy decreases as a rule with the extent of time over which our predictions extend. The chief reason is that there may be certain factors at work which are unknown and relatively insignificant for a short time, but which in the long run become very important. Thus, in the case of the climate at a particular point of the earth, we can predict the changes of seasons and of day and night and the mean temperatures with a considerable degree of accuracy for a short and also for a very long time if we know all the factors involved. But if there is some unknown cause which will continually lower the temperature of the sun at a very slow rate, then our predictions will be almost true only until sufficient time has elapsed for this unknown cause, operating in one direction, to produce important results.

A theory of evolution is extremely valuable in many ways and at the present time is considered as having a legitimate place in the discussion of every science. In the first place, it shows us what facts are important and what are not, because, in attempting to develop a theory of the changes through which a system goes, we must relate all the facts to one another. If there are any contradictions among them, and among minor theories based upon them, they will be revealed in our attempts to weave all of them together into one systematic, harmonious whole. For example, if our conclusion, based on more or less uncertain observations, that Mercury has one face always toward the sun contradicts something fundamental in the system, we should be likely to find it out in the consideration of its evolution. Therefore, if we are considering only the facts and minor conclusions regarding any domain of science, we see that the attempt to construct for it a theory of evolution is of the highest importance because it compels a more careful examination of these things which we are supposing are important.

In a somewhat similar manner the consideration of a question in a large way often directs our attention to gaps in our knowledge which ought to be filled. In the biological sciences the theory of evolution has directed inquiry in thousands of directions to supply additional data. While this has not been true in astronomy to the same extent, yet the theory of evolution has there raised many new questions and stimulated important investigations.

A theory of evolution is also valuable in that by discovering what the conditions will be in the future it makes it possible for us to adjust ourselves to them, or in some cases to control events for our good. An example of this, a matter of such universal experience that it has become commonplace, is that in the summertime we prepare for the winter because we know that it is sure to come. In a larger way, particularly in the biological sciences, it may be possible to foresee things in the remote future for which we as a race should prepare ourselves.

Finally, a theory of evolution is of importance for the satisfaction it gives in contemplating the subject as one grand whole. It is related to separate facts and minor theories upon which it is based as a beautiful and finished house is to unsightly heaps of stone, brick, and wood from which it might be built. Laplace commenting on the satisfaction obtained in considering astronomy as a unit, said: "Contemplated as one grand whole it is the most beautiful monument of the human mind, and the noblest record of its intelligence."

Historical. The theory of the evolution of the solar system, and, indeed, of all the stars that fill the sky, was first begun in what would now be considered an approximately scientific manner by Thomas Wright of Durham, England, who published a volume on this subject in 1750. He supposed that the Milky Way was composed of a vast number of solar systems similar to our own, spread out in a great double ring which rotated around an axis perpendicular to its plane. He treated the solar system as an example illustrating the dynamics of the sidereal system. His work was not adequately based on observations and contained many serious errors. This, of course, was only to be expected in pioneer work in so difficult a subject.

The work of Wright fell into the hands of the brilliant philosopher Kant, who was then a young man. His vivid imagination quickly ran beyond the bounds of what Wright had set forth. He saw some of the weaknesses of Wright's theory and the possibility of adding greatly to it. In 1755, he published a book on the subject agreeing in many respects with that of Wright, but which, on the whole, was vastly superior to it. He supposed that in the beginning all the material which now makes up the sun and planets and other members of the solar system was in a widely-scattered primitive condition of un-united elements. He supposed that the chemical affinity of one element for another caused compounds to be formed, thus setting up motions. As atom united with atom to make compounds, so molecule united with molecule under gravitative forces and made continually larger and larger masses. As masses of considerable dimensions were formed so that they became strong centers of attraction, considerable motions were developed. In some obscure way he supposed the motions in all directions, except that in which the planets moved, were destroyed by collisions, leaving a number of planets revolving in a definite plane. Kant considered in successive chapters of his book the densities and rotations of the planets, the eccentricities of the orbits, the origin of comets, the origin of satellites, the origin of the rings of Saturn, the zodiacal light, and the theory of the constitution and condition of the sun.

The beauty and generality of Kant's theory, as well as the attractive manner in which he set it forth, are very enticing, but when considered calmly in the light of modern knowledge, particularly in the light of dynamics, it is found to have some serious and fatal faults. Notwithstanding this, there are many very valuable contributions in it to the subject, and it is a stimulating book to read even at the present time.

The world was not prepared for the ideas of evolution in 1755, and the work of Kant attracted only very little attention. But in 1796 a great French astronomer, named Laplace, at the end of a charming popular book on astronomy, explained in a few pages his ideas of how the solar system may have arrived at its present condition. This was written apparently without any knowledge on the part of Laplace of the work of either Wright or Kant. Laplace introduced the discussion by calling attention to the remarkable regularities in the solar system. He commented on the fact that the planets all revolved around the sun in the same direction nearly in the same plane. He calculated that this condition would be the result of chance only once in some 500,000,000 cases, showing, therefore, that in all probability it was due to some initial state from which it had systematically developed. He likewise called attention to the remarkable circularity of the orbits and the directions of rotation of the planets, etc.

In outline the theory of Laplace is that originally the solar atmosphere was a nebulous envelope in an intensely heated condition, and that it extended out beyond the orbit of the farthest planet. He supposed the whole mass rotated as a solid in the direction in which the planets now revolve. It was supposed in this theory that the dimensions of the system were maintained by gaseous expansion the same as the dimensions of the sun or the earth's atmosphere are at present. This great nebulous mass would lose heat by radiation into space and consequently would contract. If such a rotating mass contracted, it would continually rotate faster and faster for the reasons set forth in discussion of the question of the uniformity of the earth's rotation. If a mass rotates faster, the tendency for the material at its equator to fly off because of the centrifugal acceleration continually increases. Laplace said that it seemed reasonable that the contracting solar mass would reach such a state that this tendency of the particles at its equator to fly out would exactly balance their tendency to go in because of the attraction of the mass interior to it. When this state was reached he supposed a ring would be left off, as is indicated in Fig. 107.

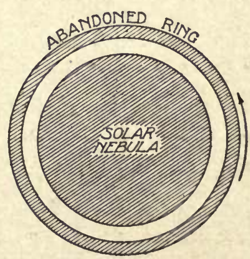


Fig. 107. The Laplacian Ring Theory of the Origin of the Planets

Unless the ring were perfectly circular and uniform, and subject to no disturbing influences, it would have a tendency to break, Laplace thought, at some place and to concentrate on the place in it where there was the greatest mass. That is, if there were a nucleus on it at any point, this excess of matter would gradually draw to it all the rest of the whole ring, while it would continue to revolve around the sun in the same period as the ring did at the time it was abandoned. It seemed to him probable that the sun would go on shrinking after a ring was abandoned and that it would later leave off another, and then still another similarly, until it either arrived at a state of permanent equilibrium or had a density so great that it could no longer contract.

Laplace then supposed the system of planets grew up from a system of rings abandoned successively by the sun, beginning with the outermost and ending with the innermost. The rings concentrating would give rise to large, globular masses revolving around the sun at their respective distances from it. These globular masses might in turn be rotating so rapidly that they would abandon rings which in a similar manner would give rise to satellites. He supposed that perhaps Saturn's rings were examples of this process in which the satellites were not yet formed.

This theory of Laplace pictures the earth as being at one time in a gaseous state. It was supposed that by losing heat it cooled off until a crust formed over its surface, leaving the liquid interior; and it was thought that the volcanoes were openings through the shallow crust into that liquid interior. This theory was widely accepted: *first,* because of the great name of its author; and *second,* because of its simplicity and harmony with the main facts of the system. It gave the geologists reasons for believing that the earth is very old, and encouraged them to draw conclusions respecting its age and evolution on the basis of geological facts. The half century following Laplace's work was characterized by most remarkable activities in geological science. The great age of the earth was fully established, and the innumerable fossils which filled the old rocks were brought to light in vast numbers. The work of the geologists paved the way for the zoologists. In 1858, Darwin extended the general ideas of evolution, which had their origin in astronomy and which had spread to geology, to the biological sciences by his publication of the "Origin of Species." It is questionable whether any other work of modern times has had so profound an influence on the thought of the world as this book by Darwin. Since its publication the doctrine of evolution, aside from the details of its precise mode, has been almost universally adopted. Not only is science considered from the point of view of a changing universe, but history is interpreted in the light of it and its applications are extended to the political and social sciences, and even to religion.

Test of the Laplacian Theory. There are two general ways of testing the truth of a theory. One is the determination of whether it is consistent with itself, and the other is whether it is in harmony with the facts given by observations. The former is generally the more difficult of the two, and in questions of physical science is largely of a mathematical nature.

As Laplace himself pointed out, his hypothesis as to the ring origin of the planets is in agreement with the chief facts of the solar system. If the solar system originated in this fashion we should expect all the planets to be revolving in the same plane, or at least nearly in the same plane, and such is the case. If there were any deviations from strict agreement of the planes of revolution due to any irregularities in the original solar nebula, we should expect to find the greatest ones in the planets far from the sun, because as the sun continued to rotate there would be a tendency for it to become more and more uniform. Here the consequences of the theory are not so well in harmony with the facts, for the orbits of the remote planets are on the whole much more nearly circular than those which are closer to the sun. Mercury has a more eccentric orbit than any other planet. According to this theory the planets should all revolve around the sun in the same direction, and this is found to be true in the solar system. According to the Laplacian theory the orbits should be very nearly if not exactly circular, and this is also almost verified in the solar system. If there were any deviations from sensible circularity it would be expected, according to the theory, that they would be the greatest in the case of the orbits of those planets which were far from the sun. Here the theory is not in so perfect harmony with the facts, because it is found that the orbits of the remote planets are on the average more nearly circular than those closer to the sun, and that Mercury's orbit is the most elongated of all.

While the Laplacian theory is in general harmony with the main facts furnished by observation, there are, nevertheless, some respects in which it is not entirely satisfactory. The question arises whether they are not sufficient to compel us radically to modify it. It is understood that it is easier to disprove a theory which is wrong than it is to establish one which is correct, for one example contradictory to an erroneous theory disproves it, while many examples of harmony with a correct theory only show that it is probable. A slight disagreement between the ring theory and the planes of the orbits of the planets and their eccentricities have been noted. There is much more serious disagreement when we come to a consideration of the orbits of the planetoids, which were not known when Laplace first formulated his theory. There are now about 700 known planetoids whose orbits vary from coincidence with the plane of the planetary orbits, to an inclination of nearly 40 degrees to it, and from sensibly perfect circularity to elongations nearly as great as those of some of the cometary orbits. These 700 orbits weave in and out among one another in such a fashion that if they were made of wire one could not be removed without taking all of them. According to the ring theory it is necessary to suppose that a ring was abandoned for each one of them. It is perfectly obvious that so complex a ring system intersecting itself, is entirely outside of the possibilities. For example, the orbit of Eros reaches out beyond that of Mars and down almost to that of the earth, and is highly inclined to the orbits of both planets. The ring theory asks us to suppose that a ring was abandoned, which later went into the planet Mars, then another highly inclined to the former and reaching beyond it, which went into the planetoid Eros, and then another from which the earth developed. The impossibility is apparent.

Objections of quite another type are presented in the case of the satellites of Saturn and Jupiter. Each of these planets has a single satellite revolving around it in the retrograde direction. According to the Laplacian theory of the origin of the satellites, rings were abandoned at their respective distances and the planetary nebula contracting later abandoned more rings. It follows from this theory that all the satellites must necessarily revolve around their respective planets in the same direction. The fact that this is not so in two cases is a direct contradiction of the theory.

It has been stated that as a body contracts it rotates faster and faster. Consequently, since by the Laplacian hypothesis the planets have contracted from the dimensions of their satellite orbits, every planet must rotate in a shorter period than that of the revolution of its innermost satellite. This certain consequence of the theory is violated in the case of the inner satellite of Mars, which makes its revolution in about eight hours while Mars turns on its axis in a period of some 24 hours. There is also an important discrepancy between theory and observations in the case of the inner ring of Saturn, the particles of which make a revolution in about five hours while the planet rotates on its axis in a period of a little more than 10 hours.

According to the Laplacian theory, the more remote planets are older than the interior ones. The excess of their ages is not known, but certainly it must be very great according to the theory. Perhaps Saturn is a thousand times as old as the earth. When we consider how much greater its orbit is than that of the earth, and how long it must have taken the sun to contract from the dimensions of the earth to its present size, this does not seem an unreasonable estimate. It follows that if Saturn were originally in a state similar to that of the original earth it should be much farther advanced in its evolution. It was seen in the discussion of planets that Saturn is yet in a very primitive state. Of course, being larger, it would undergo its evolution more slowly, but it seems to strain the probabilities of the matter to suppose that its difference in size could offset its supposed great difference in age. It is thus seen that the Laplacian theory is in many places in direct conflict with the observations. These discrepancies, however, have nearly all been discovered since the theory was originally formulated.

About ten years ago Professor Chamberlin and the writer undertook to make a critical examination of the Laplacian theory, both for internal discords and harmonies, and to find disagreements and agreements with the facts given by observation. This study revealed inconsistencies in the theory itself, as well as contradictions to the observed phenomena, some of which have been noted above, which compel its radical modification. It is certain now that the ring hypothesis as to the origin of the planets can no longer be held as a possibility. This does not mean that the Laplacian theory has not been of the greatest importance in the development of science, but it simply indicates that greater knowledge has shown us its imperfections, and how we may use it as a stepping-stone to a more perfect picture of the origin and evolution of the solar system.

Planetesimal Theory. The solar system exists and is in the midst of an evolution; the problem is to trace out the mode of this evolution. The Laplacian theory has been seen to have fatal weaknesses and to be no longer tenable. We shall now outline a theory which has been developed by Professor Chamberlin and the author to take its place.

Instead of supposing that the solar system started from a vast gaseous mass in equilibrium under the law of gravitation and the laws of gaseous expansion, the Planetesimal Hypothesis postulates that the matter of which the sun and planets are composed was at a previous stage of its evolution in the form of a great spiral swarm of separate particles whose positions and motions were dependent upon their mutual gravitation and their velocities. Gaseous expansion preserved the dimensions of the Laplacian nebula but had no sensible influence in the spiral. Because of the fact that every particle according to this theory is considered as being an essentially independent unit it is called the *planetesimal* theory. Before considering in detail the planetesimal hypothesis, and before proceeding to a discussion of its merits, attention should be called to the fact that there is not in all the heavens a single example known of a nebula of the Laplacian type. On the other hand, recent discoveries, particularly those made at the Lick Observatory, show that the spiral nebula is not only a common form but is, indeed, the dominant type. There are within range of our instruments at least ten times as many of them as of all other types combined, and they range in extent and brightness from the great Andromeda nebula down to small faint masses which are barely distinguishable with long exposure photographs taken with the most powerful instruments.

Before considering the evolution of our system from a spiral nebula, a suggestion as to its origin will be developed. It is, of course, understood that the theory is independent of the correctness of this suggestion. It has the merit of giving us a full picture of the course of evolution and of showing the dynamical condition of a nebula. It has been seen above that there are within the range of our present instruments at least a hundred millions of suns, and it is found, from the observations of their apparent motions and their actual motions in the line of sight by means of the spectroscope, that on the average they are moving with high speed. Though there are undoubtedly parallelisms and some degree of orderliness in their motions, nevertheless, it is almost certain that now and then two suns will pass near each other. A computation, based on suppositions which seem to be reasonable as to the dimensions of the sidereal system and the number of stars in it, shows that in the long run a given sun will

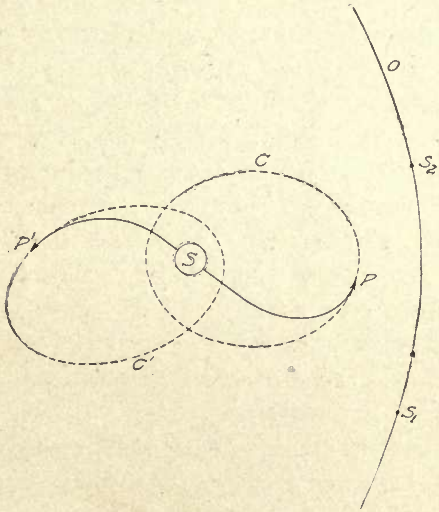


Fig. 108. The Origin of Elliptical Orbits of Matter Ejected from the Sun at the Time a Star is Passing

pass near enough to another sun to cause serious disturbances about once in a billion years.

Now consider a star passing near our sun, and remember that the latter is a highly heated body subject to explosive forces which even at frequent intervals hurl matter up from its surface to heights of several hundred thousand miles. In Fig. 108 let S represent our sun, and O the orbit of a star passing by it. Consider the visiting star when it is at the position S_1. It raises enormous tides on our sun, their height depending upon its distance and mass. One tide is on the side toward S_1, and the other tide on the opposite side. Instead of being a few feet high, it is reasonable to suppose that they are many thousands of miles high. The ejections from our sun under those circumstances are most violent and to the greatest distances in the directions toward and away from S_1. For simplicity, let us consider only the matter ejected toward S_1. If S_1 were standing still this matter would proceed toward it a certain distance, depending upon the speed with which it left the sun, and then would either fall back upon the sun or go to S_1, depending upon which had the dominating attraction for it. But instead of standing still S_1 is moving forward rapidly in its orbit. Suppose the direction of motion is that indicated by the arrow in Fig. 108. After a certain interval S_1 has moved forward to the point S_2. At this place it is attracting the ejected mass P nearly at right angles to its original line of projection. Consequently, it causes its orbit to curve in the direction in which S_1 is going. The visiting star will go on in its

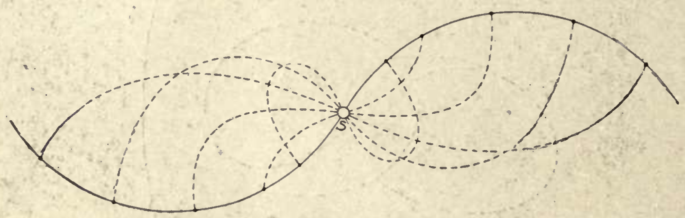


Fig. 109. The Origin of a Spiral Nebula

orbit and leave P behind revolving around the sun in the dotted ellipse C. In a similar manner the mass P will be bent from the straight line of its ejection in the direction indicated in the diagram, and will be left revolving in the ellipse C'. Therefore, as the visiting star passes near the sun it stimulates the ejection of material and causes it to deviate from the original line of its motion so that instead of falling back on the sun it is left revolving about it in elliptical orbits.

This process of ejection obviously would not take place at only one instant, while S_1 was passing our sun. We now consider the result of its taking place continually during the passage. Many particles are ejected and they move along the dotted lines of Fig. 109. At a given time they are on the full lines of Fig. 109, which are seen to constitute the arms of a spiral with two approximately symmetrical parts. If this theory is correct, we should find that the spiral nebulas have two arms reaching out from a central sun in opposite directions which are curved in the same direction. The particles on the spiral are not moving along its arms, but approximately at right angles to them. The particles near the center move faster than those far away, and consequently the older the spiral nebula and the larger its central mass relatively to the total mass of the scattered material, the closer is its coil.

Fig. 110. Spiral Nebula in Canes Venatici. Photographed at the Yerkes Observatory

The question now arising is whether the spiral nebulas which are known have the characteristics which would be predicted according to this theory. Fig. 110 is a photograph of one of these objects. It is seen that it is composed of two arms, in a general way symmetrical, which reach out from the opposite sides of a central nucleus, or sun. It is found that they always have two arms which can be more or less definitely made out, radiating from the center in this fashion. The suggestion of their origin seems to be in harmony with their appearance, though it can not be regarded as demonstrated that this is the true explanation of their mode of development. Fig. 111 shows one of these objects which is edgewise

Fig. 111. Spiral Nebula in Adromed Seen Edgewise. The Dark Peripheral Material Causes a Dark Streak by Eclipse. Photographed at the Lick Observatory

to us. The dark streak down it is due to opaque, cooler absorbing material on its periphery.

According to the planetesimal theory the planets grew up around the nuclei on the arms of the spirals from which our system developed, whatever may have been its origin. It is clear that if the origin of the spiral were as outlined above, we should not expect to find the arms perfectly uniform because the ejection from our sun would not take place uniformly. The photographs show many irregularities and local condensations on the arms. These nuclei circulating around the central sun and crossing the orbits of many other particles also circulating around the center. gradually sweep them up and in the course of time absorb all of the small masses in the system whose orbits they cross. In this manner there eventually evolves a system consisting of a central sun and a number of large masses spaced out so that they never approach very near one another, and no small ones except possibly in zones which were not occupied by any dominant nucleus.

Let us see whether this theory is in harmony with the chief facts presented by the solar system. According to it all the planets should revolve in the same direction, and such is found to be the case. According to it their planes should be approximately the same, though not necessarily the same, for the initial ejections would not necessarily be exactly toward or from the passing sun. Here, again, the theory and observations are in harmony. According to this theory the planets are all the same age, and the differences in the state of their development are only because of their different dimensions and different constitutions. The facts given by observation are in this respect much more in harmony with this theory than with the Laplacian. One of the difficulties, at least at first thought, arises from the fact that when the visiting sun had passed on, the orbits of the individual nuclei and particles should be on the average considerably more eccentric than the orbits of the planets. But a mathematical examination of the question shows that the orbits of the planets become more nearly circular on account of their collisions with the scattered material which the planets sweep up in their motions around the sun. Consequently, the more a planet grows by the accretion of this scattered material the more nearly circular its orbit becomes. It is significant that in our system the great planets all have very nearly circular orbits, while the smaller ones have more elongated orbits, and the orbits of the planetoids are in many cases very much elongated. There is here perfect harmony between the theory and the facts given by observations. Similar results follow when we consider the inclinations of the orbits to one another. The more matter a planetary nucleus acquires by collision with the scattered material, the more nearly will its orbit fall into the average plane of the system. It is found that the great planets move in orbits which are almost in the same plane, while the smaller ones deviate some, and in many cases the planetoids very much. Thus, again, there is harmony between theory and observations.

In discussing the Laplacian theory, it was found that difficulties arise because of the retrograde revolution of certain satellites. The question arises whether the planetesimal theory has difficulties in this same respect. According to the planetesimal theory the satellites have evolved from small secondary nuclei which were revolving around the central sun in close proximity to the larger nuclei which developed into planets. There is no reason why these secondary nuclei should not originally have revolved around the planets in any direction. A discussion of the matter shows that those which revolve in any direction except in that in which the planet revolves have a tendency, because of collisions with the scattered material, to fall upon the planet and to become a part of it. This is particularly true unless they are far from it. Consequently, we should expect to find the satellites on the whole revolving in the forward direction, though not necessarily all in that direction. And furthermore, there is no reason according to this theory why a satellite should not revolve around the planet in a shorter period than that of the rotation of the planet itself.

According to the Laplacian theory it is difficult to account for the forward rotations of the planets. The forward rotation of the planets is to be expected under the planetesimal theory, because it can be shown that the collisions of the scattered material with the planetary nuclei have, on the average, a tendency to make them rotate in the direction of their revolution. This tendency is, besides, the greatest in their equatorial zones, and if they are in a fluid state should give to their equators a greater speed of rotation than to the higher latitudes. All of these consequences of the theory are in perfect harmony with the facts.

Conclusion. We shall sum up in a few words the general picture of the origin and development of astronomical bodies, remembering, however, that the problem is a vast one and that the chances for actual errors and imperfections in our theories are very great. We regard matter as being in its most primitive state when it is spread out in widely-scattered, irregular nebulas. (See Fig. 104.) These objects are supposed to develop continually; that is, they are supposed not only to have originated in the past, but are even now being evolved, and will continue to evolve in the future. These nebulous masses, under the chemical and gravitational forces, became organized into suns and systems of suns. The suns now and then passing near one another develop spiral nebulas. The nuclei on the arms of the spirals, sweeping up this finely scattered material, grow into planets, or at any rate into bodies secondary in dimensions compared with the central sun. The length of time required for this evolution is altogether beyond calculation at the present time. Considering the earth, we think of it as having grown up rapidly at first, and more slowly later, by the accretion of the scattered material. Originally it was perhaps too small to hold an atmosphere, which was subsequently acquired by the expulsion of gases from the material of which it was composed, as it ground together under pressure and became heated by its contraction. After acquiring an atmosphere and water it became habitable, at least for low forms of life. At the present time it is not growing at a sensible rate, and so far as can be seen will remain approximately in its present state for an extremely long time. It seems to be threatened only by a possible failure of the sun's light and heat. Until we know more exactly than at the present time the sources of the sun's heat, we can not estimate how soon the changes in the amount of light and heat received from the sun will have sensible influences upon the earth. One event in the remote future seems probable, if not certain. It is that once again our sun will pass near some other sun, when the present planetary system will be destroyed, perhaps to give place to a new one running through a somewhat similar cycle.

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